Aircraft Measurements of Electrified Clouds at Kennedy Space Center

Final Report: Part I
1988 Flights

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1 Introduction

The space-vehicle launch commit criteria for weather and atmospheric electrical conditions in use at Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC) have been made quite restrictive because of the past difficulties that have arisen when space vehicles have triggered lightning discharges after their launch during cloudy weather. With the present ground-based instrumentation and our limited knowledge of cloud electrification processes over this region of Florida, it has not been possible to provide a quantitative index of safe launching conditions. As a result the following restrictions have been placed on space vehicle launches.

Natural and Triggered Lightning Constraints

The launch weather officer must have clear and convincing evidence the following constraints are not violated.

DO NOT LAUNCH IF:

A. Any type of lightning is detected within 10 nmi of the launch site or planned flight path within 30 minutes prior to launch unless the meteorological condition that produced the lightning has moved more than 10 nmi away from the launch site or planned flight path.

B. The planned flight path will carry the vehicle

  (1) through cumulus clouds with tops higher than the $+5$ °C level; or

  (2) through or within 5 nmi of cumulus clouds with tops higher than -10 °C level; or

  (3) through or within 10 nmi of cumulus clouds with tops higher than the -20 °C level; or

  (4) through or within 10 nmi of the nearest edge of any cumulonimbus or thunderstorm cloud including its associated anvil.

C. For ranges equipped with a surface electric field mill network, at any time during the 15 minutes prior to launch time the one minute average absolute electric field intensity at the ground exceeds 1 kilovolt per meter within 5 nmi of the launch site unless:

  (a) There are no clouds within 10 nmi of the launch site; and

  (b) smoke and ground fog are clearly causing abnormal readings.

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D. The planned flight path is through a vertically continuous layer of clouds with an overall depth of 4,500 ft or greater where any part of the clouds is located between the 0 °C and the −20 °C temperature levels.

E. The planned flight path is through any cloud types that extend to altitudes at or above the 0 °C level and that are associated with disturbed weather within 5 nmi of the flight path.

F. Do not launch through thunderstorm debris clouds, or within 5 nmi of thunderstorm debris clouds not monitored by a field mill network or producing radar returns greater than or equal to 10 dBZ.

GOOD SENSE RULE

Even when constraints are not violated, if any other hazardous conditions exist, the launch weather officer will report the threat to the launch director. The launch director may hold at any time based on the instability of the weather.

While these restrictions appear to eliminate any significant hazards arising from lightning strikes, they also reduce greatly the opportunities for launches. Atmospheric electrical hazards do not always exist during the weather conditions specified in the above criteria but when they do occur, the charges that cause them may be difficult to detect from the ground due to their localized nature and to screening by other distributions of charge. If better knowledge of the electrical conditions aloft over the launch area were available on a timely basis to the meteorologist advising the launch director, more launches could be made during periods with cloudy weather containing no electrical hazards. Airborne measurements of the electricity in clouds are therefore desirable so that an evaluation can be made of the hazards associated with the various weather conditions now prohibited in the launch commit criteria. The necessary measurements can be made with the use of a suitably instrumented airplane.

During the fall of 1988 an airplane equipped to measure electric field and other meteorological parameters flew over Kennedy Space Center in a program to study clouds defined in the launch criteria, quoted above. The study was carried out with the support and guidance of Col. John Madura, Commander of Detachment 11, 2nd Weather Squadron, USAF, at Patrick Air Force Base (PAFB) and Cape Canaveral Air Force Station. The research group included our Air Force liaisons, Capts. T. Strange and M. Jordan, and National Aeronautics and Space Administration (NASA) personnel Ms. Launa Maier and John McBrearty of Kennedy Space Center. Operational support provided by Air Force and NASA personnel included weather forecasts and weather and surface electric field information, radar plots, and satellite photographs of the clouds. The area of interest for the study and its principal geographic features are shown by the map in Fig. 1. New

Mexico Institute of Mining and Technology (NMIMT) provided the instrumented airplane (the Special Purpose Test Vehicle for Atmospheric Research, or SPTVAR) and a ground station that received and recorded telemetered data and housed the flight controllers. The airplane and ground station were based at Patrick Air Force Base from 12 September through 11 November 1988.

SPTVAR is a Schweizer 845 airplane suitable for flights through thunderclouds and is instrumented to measure all three components of the ambient electric vector. Five electric field meters, whose locations are shown in Fig. 2, are used to deduce the electric vector, the charge on the aircraft, and an estimate of the validity of the measurements. In addition, as listed in Table 1, the aircraft has instruments to measure the ambient air temperature, cloud liquid water content (LWC), atmospheric pressure, and air speed. SPTVAR is equipped with a VOR/DME navigational radio and a Loran C receiver that provides accurate airplane positions. Readings from gyroscopes are recorded to give information about the airplane's attitude (heading, roll, and pitch angles).

Basic flight parameters are as follows.

Endurance:	SPTVAR normally makes flights with durations of 3 to 3.5 hours
Altitude ceiling:	Approximately 9,000 m (30,000 ft)
Flight speed:	About 50 m/s (~97 knots)
Payload:	Pilot, fuel, and installed instrumentation.

In much of this report numerical quantities are quoted in SI units (with values in conventional units following between parentheses where appropriate). In some cases pertaining to operational procedures which commonly use only conventional units the SI values are either omitted or appear between parentheses following the conventional units. Throughout this report when quoting electric field values measured with SPTVAR the sign convention used is that a positive field vector points in the direction that a small positive test charge would accelerate when under the influence of that field. A list of acronyms used in this report is included in Appendix E.

2   Project Goals

The main goals of this project are as follows.

- Develop and demonstrate techniques for measuring the electric field aloft and locating regions of charge during flight.

- Characterize the electrical conditions within and near clouds that are presently identified as a threat to space launch vehicles.

- Study the correlation between the electric field aloft and that at Kennedy Space Center's ground-based field mill network for a variety of electrified clouds.
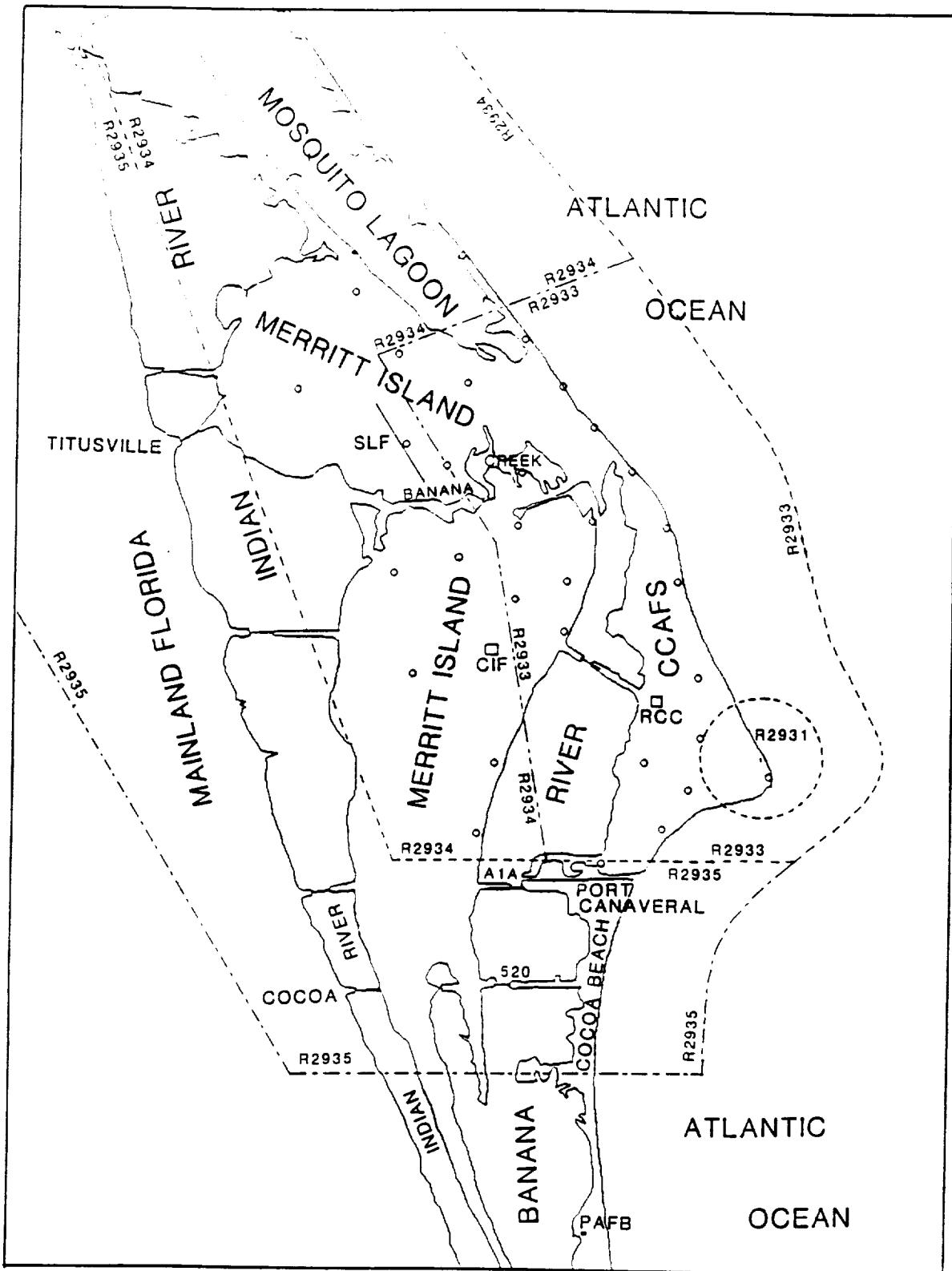
Figure 1: Map of Kennedy Space Center and surroundings showing geographic features, field mill sites (o) and restricted airspace boundaries.
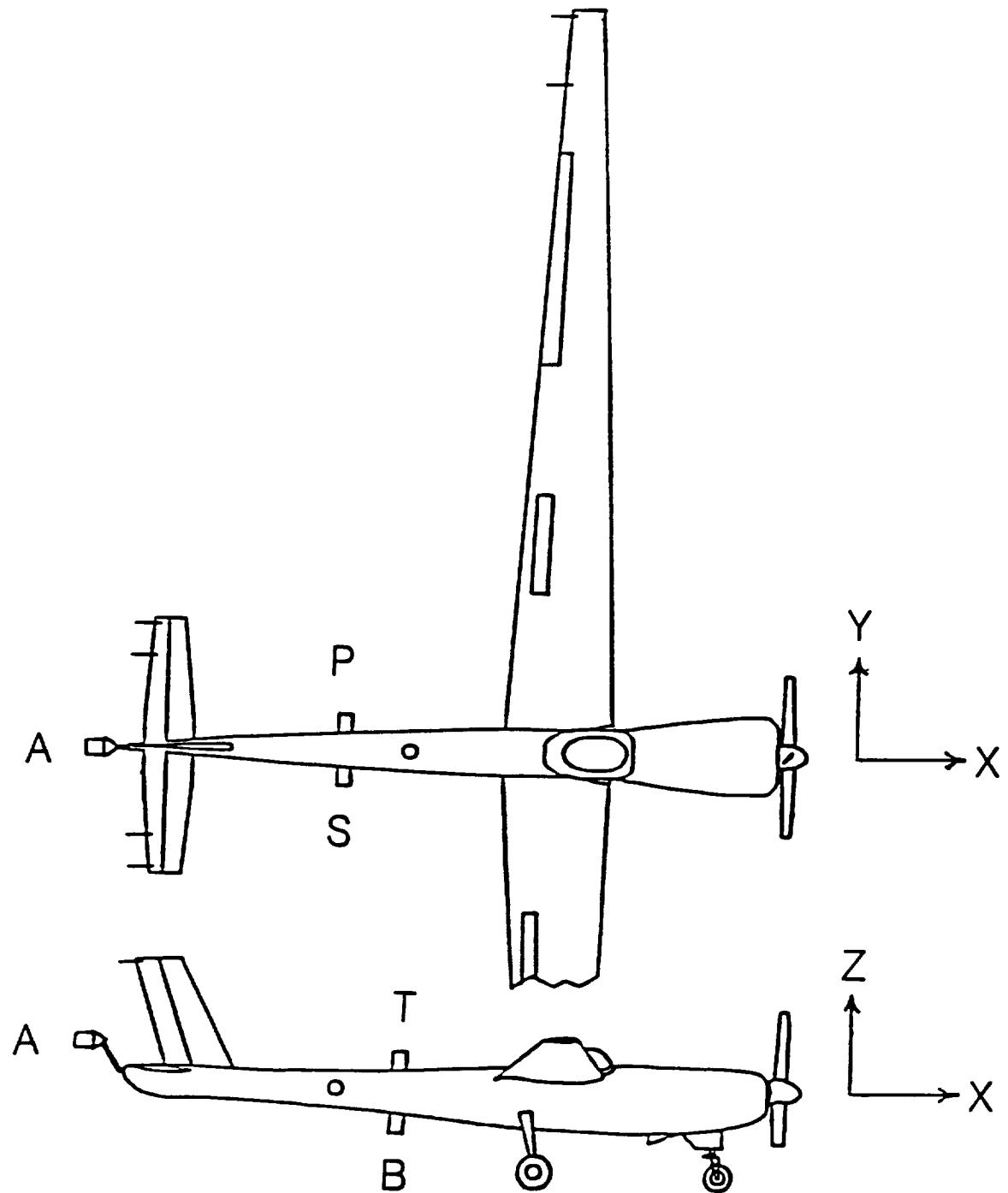
Figure 2: The Special Purpose Test Vehicle for Atmospheric Research (SPTVAR) and the airplane coordinate system. The letters **T**, **B**, **P**, **S**, and **A** identify the top, bottom, port, starboard and aft field mills which face along coordinate directions.

Table 1:

INSTRUMENTATION
§pecial Purpose Test Vehicle for Atmospheric Research
(SPTVAR)

Parameter	Instrument	Sampling Frequency
Electric field components E_x, E_y, E_z and net airplane charge Q	5 electric field mills plus 5 kV supply with current monitor	16 Hz
Liquid Water Content (LWC)	"King" probe	8 Hz
Relative ice particle concentration	Charge transfer ice probe	8 Hz
Sky brightness	Upward–looking photo cells	8 Hz
Air temperature	Rosemont temperature probe	8 Hz
Static air temperature	Platinum reverse flow thermometer	8 Hz
Static atmospheric pressure	Heise pressure transducer	32 Hz
Indicated air speed	Differential pressure transducer	8 Hz
Heading angle	Heading gyro	16 Hz
Roll angle / Pitch angle	Roll/pitch gyro	16 Hz
A_x, A_y	Two–axis accelerometer	32 Hz
A_z	Columbia 1 g offset accelerometer	32 Hz
Manifold pressure	Pressure transducer	8 Hz
Latitude and longitude	Loran C receiver	1/2 Hz

3   Flight Plans for Studying Clouds over KSC

Small Cumuli (with tops not much above the 0 °C level). Penetrate the thickest part of the cloud at some altitude approximately midway between cloud base and cloud top. Repeat penetrations to study the growth and decay of electricity in the cloud.

Lightning from warm clouds has been reported in the literature, but there have been no measurements of electric field strength inside them. Thus there is no experimental basis for predicting the altitude of the charge. If the charge is the result of convective electrification as described by Vonnegut and others, then charge should accumulate somewhere near the cloud base and cloud top and the electric field strength should be a maximum somewhere between the top and the bottom.

Medium Cumuli (with tops extending well above the 0 °C level). Make repeated penetrations around the 0 °C level to study the growth and decay of electricity in the cloud.

Charge is likely to be above 0 °C. Thus staying at 0 °C will avoid the low E_Y and E_Z components in the charge center and will also avoid icing, enabling a longer study of the cloud's development.

Debris Clouds After Thunderstorms. Fly through the debris repeatedly to study the decay of the electricity in the clouds.

Our experience in New Mexico is that charge can persist at least a half hour in debris clouds after thunderstorms have died.

Disturbed Weather (Rainclouds). Penetrate precipitation in the cloud somewhere below the 0 °C level to avoid icing. Repeat to check the time history. Fly over the top if possible to check the temperature.

Layered Clouds. Penetrate the clouds either below or above altitudes where icing will occur. If there is embedded convection, pass through it.

We expect electrification will be the result of embedded convection. In IFR (instrument flight rules) conditions, the aircraft will need radar support to locate embedded convective cells.

Anvil Clouds Blown Out From Thunderstorms. Make multiple cross-wind passes below, inside, and above the anvil if possible. Hold altitude in the anvil; climb in the turns if possible.

We suggest flying cross-wind because charge may be blown out in streamers and not extend across the entire width of the anvil.

Smoke and Ground Fog. If abnormal electric field strength readings (not fair weather) are observed over the KSC field mill network, fly as low as safety and telemetry will allow. Climb until E vanishes.

Lightning Over The KSC Field Mill Network. Fly at 6,000 ft altitude or below, within the constraints of telemetry and safety.

This will be a good situation for comparing the aircraft's electric field measurements with those at the ground.

4   Summary of Operations

When it appeared that a cloud system in the KSC airspace would preclude a launch because of a potential electrical hazard, we directed the SPTVAR aircraft to make measurements in and around that system to determine if an electric field were present and, if so, to find out as much as possible about the intensity, duration, and extent of that field.

Candidate clouds for study were chosen by the New Mexico Institute of Mining and Technology (NMIMT) scientist in charge, in consultation with NASA and USAF personnel. The NMIMT scientist was the SPTVAR pilot's operational control and assisted him in identifying the candidate cloud for study after SPTVAR was airborne. The NMIMT scientists monitored the real-time display of the computer-deduced electric field components and advised the pilot when an electric field was measured by SPTVAR. Once electrification was detected, the pilot was guided by the NMIMT scientists (in consultation with NASA and USAF personnel) in investigating regions of enhanced electric field. A special effort was made to study clouds over the field mill network at KSC.

Routine calibrations of the individual field mills were performed with SPTVAR on the ground. These calibrations are summarized in Appendix A. The gains of the mills were found to be stable to 1% while the response of the mills was found to be linear to 5 mV, the resolution of the telemetry system.

Periodic checks of the electric field measurements were conducted during the flight operations. Included were artificial chargings of the airplane during flight to check the adequacy of the charge subtraction and the functioning of the field mills. In-flight maneuvers in disturbed weather electric fields were used to check the form factors of SPTVAR. The equations for determining the electric field components and the constants used therein are summarized in Appendix B.

The values of E_X, E_Y and E_Z deduced from the field mill measurements usually are good estimates of the ambient field components. The uncertainties of the deduced field components vary from about $\pm 10\%$ for E_Z to about $\pm 14\%$ for E_Y and $\pm 20\%$ for E_X; they

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are due to the uncertainties in the determination of the form factors. There are additional uncertainties when the aircraft is highly charged and emitting ions via corona discharges.

Four voltage signals of increasing sensitivity are generated for each of the five field mills in order to cover the wide dynamic range in the strength of electric fields. The most sensitive signal often saturates and thus it is seldom used. The other three signals, which are called the "high," "medium" and "low" sensitivity signals, have useful ranges of about ± 4 kVm^{-1}, ± 40 kVm^{-1} and ± 300 kVm^{-1} respectively.

For the 1988 KSC operations, a Loran C receiver was installed on SPTVAR and interfaced to the SPTVAR encoder/telemetry system so that the Loran-determined latitude and longitude were available in the SPTVAR ground station. The precision of the Loran determination of the SPTVAR coordinates is about 100 m (on the display of the SPTVAR path on the PC monitor one can clearly distinguish the PAFB runway from the adjacent taxiway about 200 m away). The absolute accuracy of the Loran-determined coordinates was tested by overflight of prominent landmarks. The coordinates were found to agree very well (to within about 200 m) with the pilot's reported visual location. This new capability has allowed the development of new methods for displaying electric field data during flight. A key element was the development of a program for a PC-compatible computer which provides a combined real-time display of the airplane location and the deduced electric field components in clouds. A brief summary of the capabilities of this program, named "SPT," and instructions for its use are presented in Appendix C.

5 Data Display for Operations

An airplane instrumented with electric field meters can be a good platform for finding the locations of regions of charge inside clouds. However, data from a single pass through a cloud often are not sufficient. One problem is that the charge distribution is often complex and small charges near the flight path can mask the presence of greater distant charges. Another problem is that airplanes can become so highly charged by collisions with ice or water particles that the airplane itself emits charge that can disturb the measurement. Both problems can be overcome by flying the aircraft along several well chosen paths inside and/or outside of the cloud, but since clouds are large and can change rapidly no airplane has the capability of finding the appropriate paths by random sampling. A real-time display of electric vectors along the path of the aircraft provides critical information for choosing future flight paths.

As part of this program we equipped SPTVAR with a Loran C receiver for improved tracking. The receiver and interface to the telemetry system were installed and tested in Socorro, New Mexico, before the Florida operation began. Software for printing out latitude, longitude, and electric field data was in operation for the first time on 27 September

1988. We plotted SPTVAR's position during flights on a large wall chart. The Loran coordinates agreed very well with the pilot's reported visual location based on prominent landmarks.

On 7 October, SPTVAR's track was first plotted automatically on the screen of a PC-compatible computer with a program we developed and named "SPT", which is discussed in Appendix C . After some improvements in the program, we began on 30 October to explore ways of using the good tracking information to guide the pilot toward regions of interest. At first we asked the pilot to fly circular paths as a way to seek out charged regions, but this did not work well because of drift in the roll gyro. During the next flight, on 31 October 1988, the pilot flew rectilinear paths with long north-south segments separated by typically shorter east-west segments. The resulting path is shown in Fig. 3.

After the flight on 31 October 1988, the first version of SPT for plotting E_Z as horizontal barbs along the track was run on the data stored on disk for this flight (see Fig. 4). This representation or picture is a very effective visual aid for getting a feeling for the nature of the measured atmospheric field pattern along the SPTVAR ground track. When played back post-flight it made a sort of movie of the flight since the computer drew the picture on its screen much faster than it did in real time.

The flight tracks shown in Figs. 3 and 4 are difficult to follow because the airplane made repeated passes through the same airspace. Limiting the plot to selected time intervals of the flight to avoid overplotting an earlier time interval yields more easily interpreted plots of the measurements. Figure 5 shows a 21-minute segment of the flight shown in Fig. 4.

For subsequent flights the barb-drawing version of SPT was used so that both the ground track and the cloud electrification could be monitored in real time on a single display. The program SPT has an option that allows the track to be cleared from time to time so that the screen plot does not become too cluttered (see Appendix C). Refinements of SPT allowed for displaying the boundaries of restricted areas R2931, R2934 and R2935 during record mode and for the option of displaying E_Y along the track, instead of E_Z, during playback mode (see Fig. 6).

Extending this idea, we developed computer code to plot a similar diagram showing the magnitude and direction of $\vec{E}_{XY} = \vec{E}_X + \vec{E}_Y$ along the SPTVAR ground track (see Fig. 7). This type of plot will be helpful for locating regions of charge which make the greatest contribution to the electric field along the flight track.

6   Data Display – Detailed Analysis

The plot with $\vec{E}_{XY}$ barbs plotted along the flight track for 31 October, shown in Fig. 7, reveals a great deal about the charge structure of the cloud. Figure 8 is a copy of Fig. 7
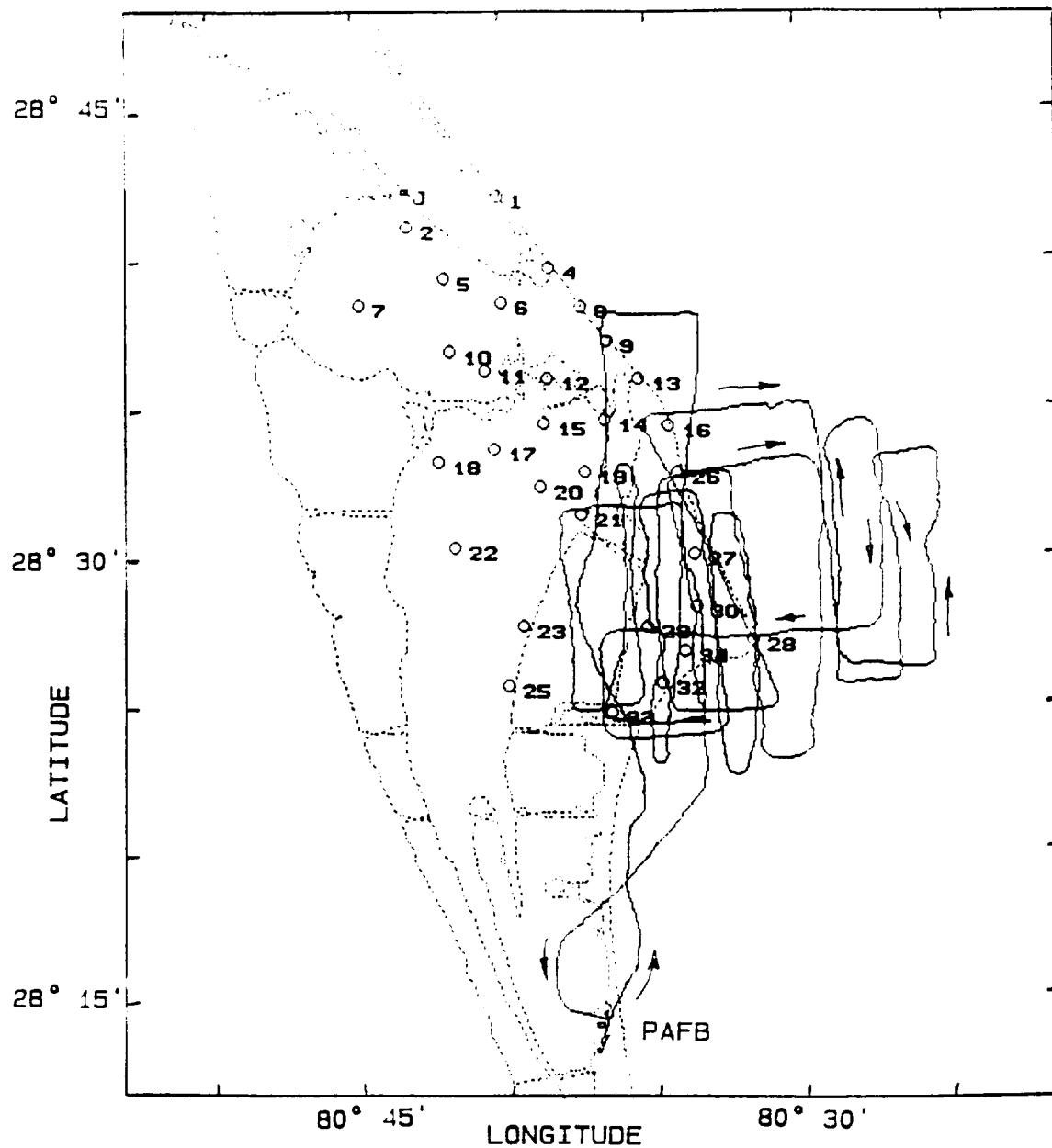
Figure 3: SPTVAR flight track on 31 October 1988. The small circles and the numbers beside them indicate the locations and site numbers of the KSC ground-based field mills. The spot labeled **J** locates the triggered-lightning rocket site on Mosquito Lagoon. The geography is shown by the faint coastal outlines; the flight track is shown by the solid line. Flight direction arrows have been added by hand.

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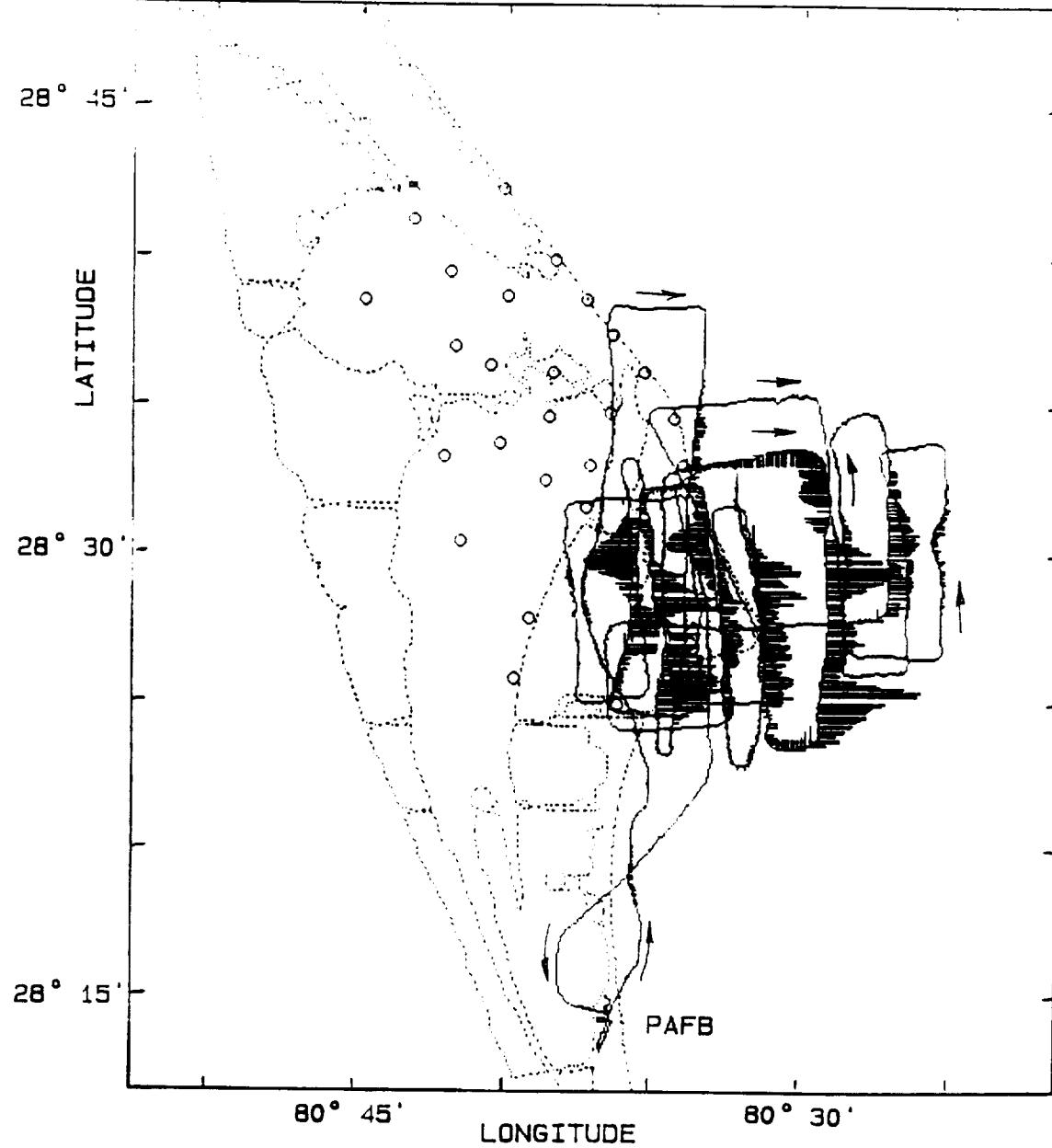
Figure 4: The 31 October flight track with the addition of barbs along the track to represent the measured E_Z. Positive E_Z is plotted toward the right in the figure.
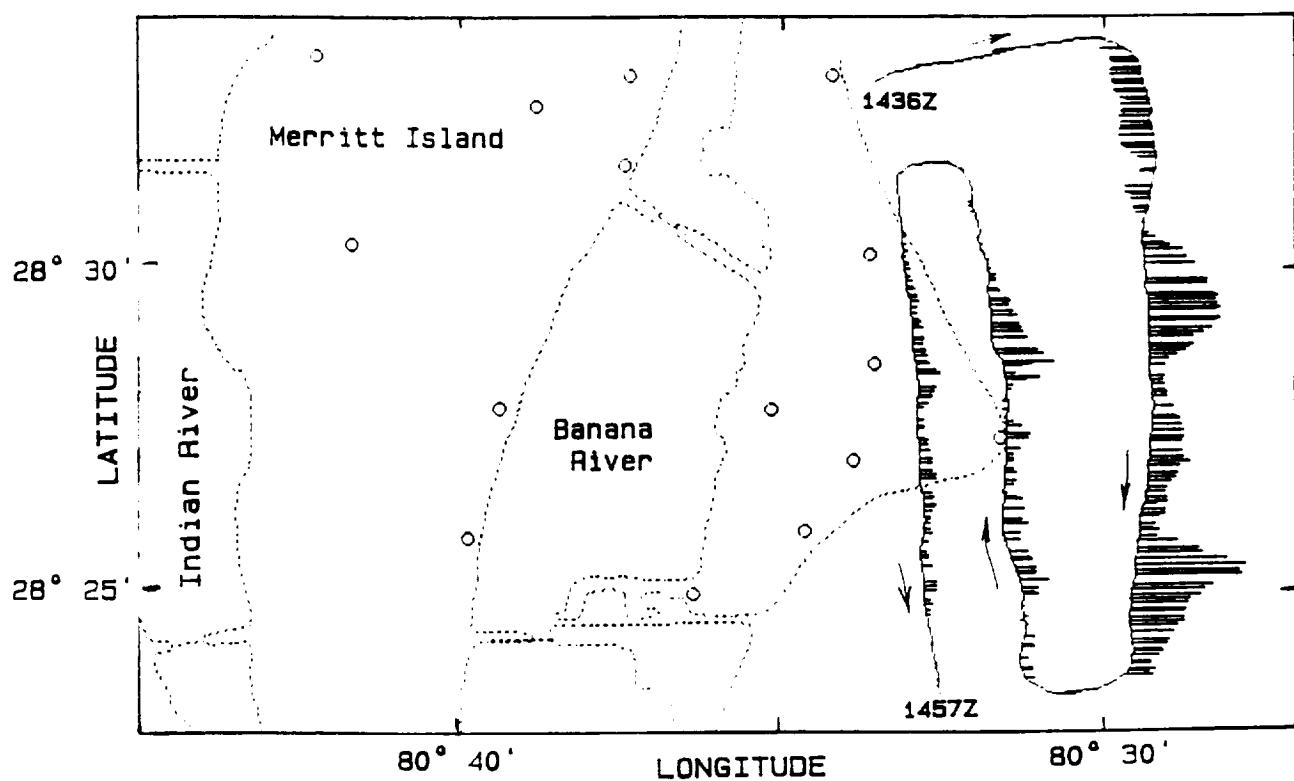
Figure 5: The 31 October flight track from 1436 to 1457 Z with horizontal barbs representing E_Z. Positive E_Z is plotted toward the right in the figure.
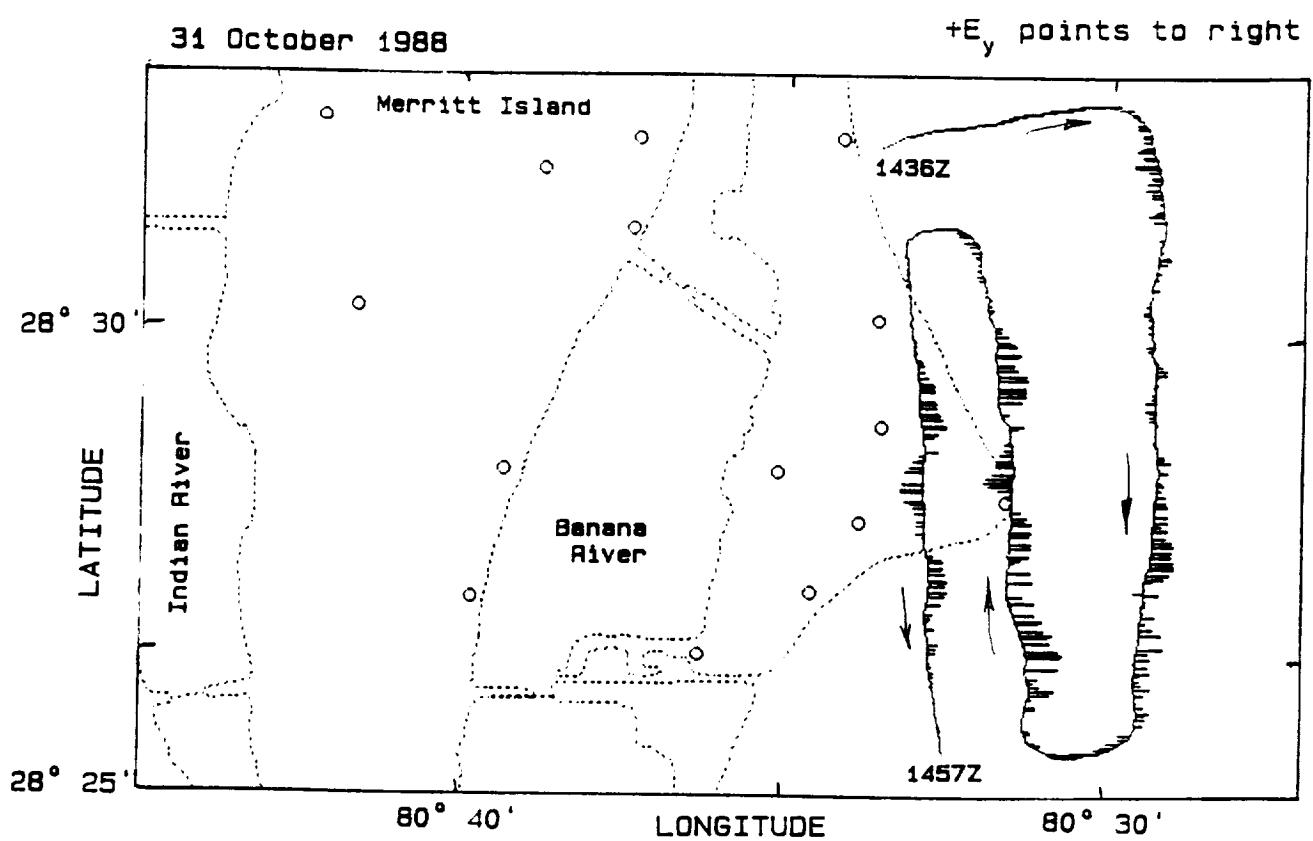
Figure 6: E_Y plotted along the track for 1436–1457 Z, 31 October 1988. Positive E_Y vectors point along the left wing.
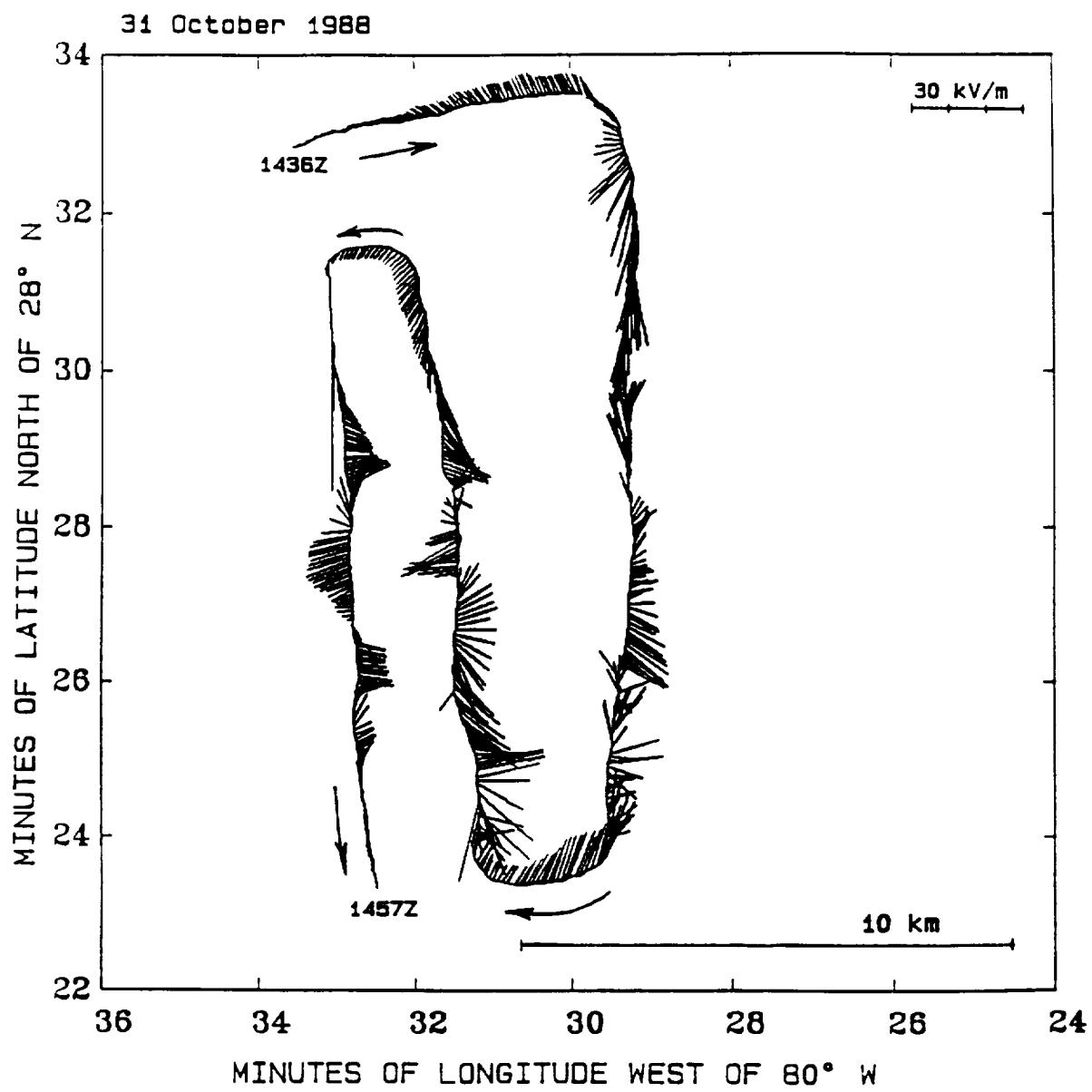
Figure 7: The same 31 October flight segment shown in Fig. 6, but with the barbs representing $\vec{E}_{XY} = \vec{E}_X + \vec{E}_Y$. Positive E_X is plotted in the airplane heading direction, and positive E_Y is plotted perpendicular to E_X, and in the direction of the left wing.

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with circles drawn in to indicate charge locations. Since, according to our sign convention, electric vectors point toward negative charge and away from positive charge, the $\vec{E}_{XY}$ barbs converge on regions with negative charge and diverge from regions with positive charge. The signs of the charges, determined on this basis, are inscribed in the circles. The letters next to the circles are used to identify the charge regions in the following discussion. The direction of flight is shown by the arrows along the track.

On the first leg of the 21-minute flight interval shown, a positive charge was off the left wing at a, a negative charge directly over or under the track at b, a region of positive charge to the right at c and a region of charge of undetermined polarity centered on the SPTVAR track at d.

On the next flight leg SPTVAR flew north and first passed positive charge off the left wing at e, then negative charge off the right wing at f followed by positive charge to the left at h and negative charge to the left at i, positive charge centered near the track at j, negative charge to the right at k, and finally positive charge at some distance to the right at l.

On the third flight leg shown there was a negative charge to the left at m, a positive charge just left of the track at n, a possible charge at o near the track and finally a positive charge to the right of the track at p.

These charge identifications are confirmed by the complementary information contained in the picture shown in Fig. 9, where the two-dimensional vector in the vertical plane, $\vec{E}_{XZ} = \vec{E}_X + \vec{E}_Z$, is plotted along the flight track. Positive E_Z, as measured in the airplane coordinate system, always points to the east (right) in this figure. Positive E_X, as measured in the airplane coordinate system, points toward the north when the general SPTVAR heading is north and to the south when the general SPTVAR heading direction is south. $\vec{E}_{XZ}$ barbs have been omitted when the SPTVAR heading direction deviated more than 20 degrees from north or south. In this plot, of $\vec{E}_{XZ}$ barbs which converge east (right) of the flight track locate negative charge overhead.

On the first flight leg shown in Fig. 9 there was a positive charge above the airplane at a, the same place along the track that a positive charge was identified in Fig. 8. There was then a very distinct negative charge above SPTVAR at b, just where a negative charge was identified in Fig. 8. The positive charge at c was below the airplane. The charge region identified as d in Fig. 8 was more complex with two positive charges below the airplane and a negative charge well above the airplane.

On the second flight leg, there were small positive charges below the airplane at e, h and j. Negative charges were above SPTVAR at f, i and k.

On the last flight leg shown the negative charge at m was above the airplane. Three subsequent regions of positive charge located at n, o and p were below the airplane.

On this day the clouds were moving toward the west-southwest. Figure 6 exhibits a

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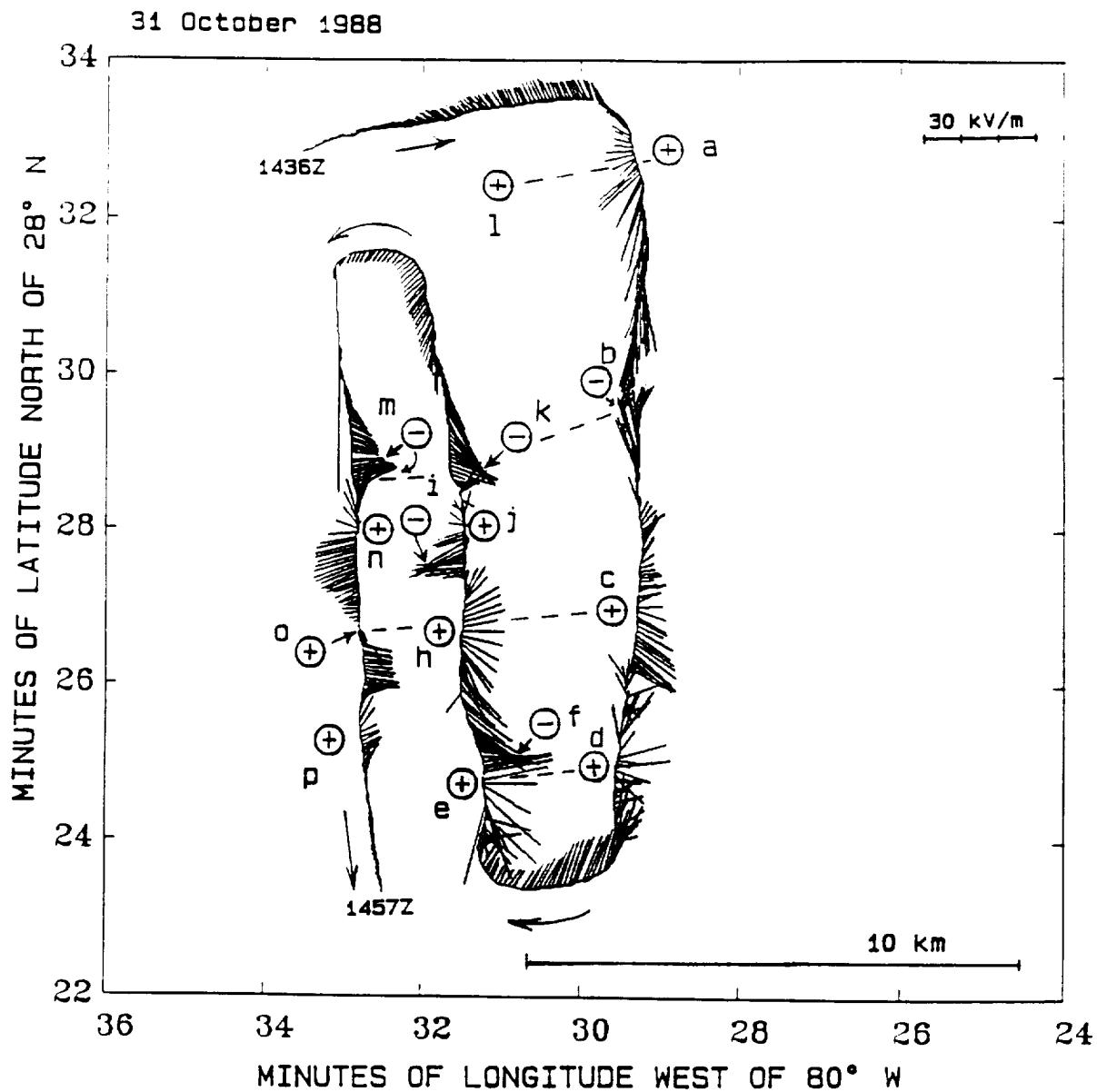
Figure 8: The SPTVAR flight track from 1436 to 1457 Z on 31 October with $\vec{E}_{XY}$ barbs plotted along the track. Positive E_X is plotted in the airplane heading direction and positive E_Y is plotted perpendicular to E_X, in the direction of the left wing. The circles indicate regions of charge, the polarity of which is shown by the sign inside the circles. The $\vec{E}_{XY}$ barbs diverge from regions with positive charge and converge on regions with negative charge. The dashed lines connect successive locations of charges as the clouds moved with the wind from the east.

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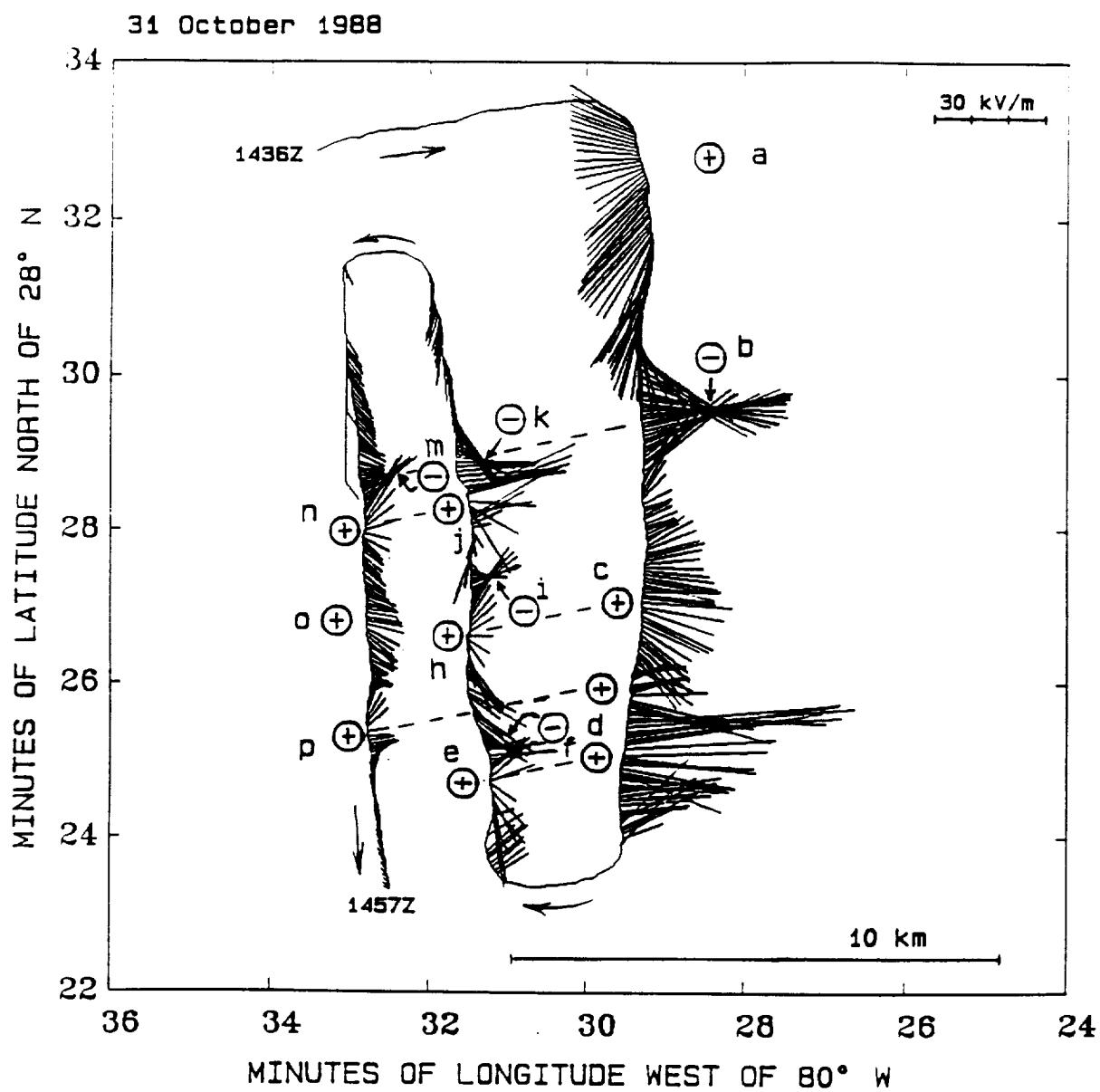
Figure 9: The SPTVAR flight track from 1436 to 1457 Z on 31 October with $\vec{E}_{XZ} = \vec{E}_X + \vec{E}_Z$ barbs plotted along the track. In this figure, positive E_Z, measured in the airplane coordinate system, is plotted to the right and E_X, measured in the airplane coordinate system, is plotted to the north for northward travel and to the south for southward travel. Barbs are only drawn if the heading angle was within ±20 degrees of north or south. Convergence of $\vec{E}_{XZ}$ barbs to the east (right) of the flight track locates negative charge overhead. The dashed lines connect successive locations of charges as they moved with the clouds.

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similarity in the barb pattern from one flight leg to the next, with a southerly shift in the pattern between flight legs. Thus it appears that the positive charges at a and l are one and the same. Similarly, the negative charges at b, k, and m were a single charge moving with the cloud as it moved onshore at the Cape. The positive charges at c, h and o and those at d, e and p, as well as the negative charges at d and f, appear to be similar repeatedly-observed charges. The dashed lines in Figs. 8 and 9 connect successive locations of charges as they moved with the clouds.

Eight distinct regions of charge in clouds have been identified in the SPTVAR data obtained during the 21 minutes of flight analyzed here. The charge structure of the clouds was complex with the largest charges being those initially identified as a and b, which were located at some distance from SPTVAR. The remaining charges were small ones located near the airplane. Overall, the charges decreased in magnitude during the time period of these measurements, and indeed later passes confirmed that the cloud charges were dissipating. The clouds did not produce any lightning, indicating that the charge must have been dissipated by conduction and precipitation. The charge structure is curious in one regard, namely the prevalence of positive charge just below the airplane altitude of 6,000 ft (1.8 km). During the active life of a thunderstorm generator, the primary positive charge is above the negative charge region and both are above the freezing level. Perhaps, since the clouds studied here did not make a thunderstorm, we should not expect them to have the same charge structure.

7   Summary of Flights

Table 2 is a summary of the 18 flights made by SPTVAR, arranged in chronological order. The Table shows the take-off and touch-down times and the range of flight altitudes during the main part of the flight. A brief comment summarizes the presence or absence of significant electric field strengths. "No E" means $|E| < 200$ V/m.

Table 3 arranges the flights according to synoptic situations and cloud types. The cloud top heights in this table are those reported by the SPTVAR pilot except those labeled with R, which are based on radar echo tops determined by the McGill radar at Patrick Air Force Base .

During ten of the flights, cumulus clouds had tops lower than the 0 °C level and SPTVAR detected no electric field strength greater than 200 V/m.

There were three examples of layered clouds other than anvil clouds. In one case (1 November) the layer was thin, extending between 1,000 and 2,500 ft (0.3 – 0.77 km) altitude with cirrus above, and SPTVAR detected no electric field strength greater than 200 V/m. In the second case (18 September) electric field disturbances coincided with embedded con-

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Table 2: Chronological Summary, SPTVAR Operations, KSC–Patrick AFB, 1988.

DAY	DATE	T-O	T-D	ALTITUDE (FEET)	COMMENTS
88258	14 Sep	2005	2106	5,000	Test flight
88260	16 Sep	1042	1231	8-10,000	No E fields
88262	18 Sep	1609	1812	17,000	Good E at times
88263	19 Sep	1835	2024	10,000	Tiny E once
88264	20 Sep	1509	1804	12,500	No E any time
88270	26 Sep	1951	2212	15,000	E_z to 50kV/m, lightning.
88271	27 Sep	1715	2018	6,000	E from anvil cloud
88274	30 Sep	1358	1658	6,000; 14,000	E, Jafferis' trigger attempts
88279	5 Oct	1454	1745	6,000; 12,000	No E any time
88280	6 Oct	1822	1913	7,200	No E any time
88281	7 Oct	1113	1346	8,000	No E any time
88282	8 Oct	1119	1307	8,000	No E any time
88288	14 Oct	1226	1332	6-8,000	No E any time
88290	16 Oct	1146	1312	8-9,000	No E any time
88291	17 Oct	1613	1909	10,000; 5,000	Tiny E late in flight
88294	20 Oct	1840	2025	6,000; 1,000	No E any time
88304	30 Oct	2003	2118	6,000	Test flight, No E
88305	31 Oct	1304	1558	6,000	Good E, Excellent flight
88306	1 Nov	1910	2055	6,000; 2,500	No E any time
88309	4 Nov	1213	1520	6,000; 11,500	Tiny E at times

Table 3: Meteorological Summary, SPTVAR Flights, Kennedy Space Center, 1988

Eastern Standard Time (EST) is 5 hours less than Greenwich Mean Time (Z).

DAY	T/O TIME (EST)	CLOUD TOPS (kft)	0, −20 °C LEVELS (kft)	COMMENTS, MAX SPTVAR E_Z
Morning cumulus associated with convergence:				
30 Sep	8:58	35	14.5, 25.5	NW–SE convergent line off NE FL coast. E_Z to +10 kV/m early in flight, and to +28 kV/m between two firings by Jafferis when SPTVAR near triggered-lightning rocket site .
5 Oct	9:54	13	14.5, 24.5	E–W convergence line, $|E_Z| < 200$ V/m.
14 Oct	7:26	8	12.5, 22.5	Convergence band along E coast, convection south of Melbourne, $|E_Z| < 200$ V/m.
16 Oct	6:46	12	14, 24	Area of convergence moved onshore, early morning Cu, $|E_Z| < 200$ V/m.
Early morning cumulus - no convergence:				
16 Sep	5:42	12	16, 26	Depressed Cu fields, clouds dissipating as aircraft approached, $|E_Z| < 300$ V/m.
7 Oct	6:13	14	14, 25	Offshore convection moved over KSC, $|E_Z| < 200$ V/m.
8 Oct	6:19	8	14.5, 24	Clouds peaked at dawn then deteriorated, $|E_Z| < 200$ V/m.
Midday sea breeze clouds:				
20 Sep	10:09	14	15.5, 26	Sea breeze front, light rain from a few Cu, $|E_Z| < 200$ V/m.
6 Oct	13:22	10	15, 25.5	Short lived Cu, $|E_Z| < 200$ V/m.
20 Oct	13:40	10	13.5, 24	Outflow clouds from offshore convection dissipated before airplane arrived, no clouds.
Sea breeze clouds enhanced by outflow boundaries:				
26 Sep	14:51	17–20	15, 25	Outflow from thunderstorms in an E–W convergence line enhanced sea breeze convection. Aircraft flew through stratus, debris clouds and anvils and saw field reversals which match ground field mills. E_Z to ± 45 kV/m.
27 Sep	12:15	12(R)	14.5, 24.7	E–W convergence line enhanced convection all day. KSC mills saw negative E below a cloud that dissipated rapidly. This field not seen by airplane. Anvil overhead from cell 25 mi to west produced E_Z to −5 kV/m. Airplane saw E_Z to +38 kV/m departing PAFB.
17 Oct	11:13	12–20	14.5, 23	Offshore convection and convergence band, showers with weak surface fields. $|E_Z| < 300$ V/m.
Clouds in an easterly flow enhanced by an upper level short wave:				
18 Sep	11:09	30(R)	15.5, 27	Stratus and altostratus with embedded rain showers moved onshore from the east. Additional convection formed over KSC. Airplane encountered strong fields in embedded convection. E_Z to ± 50 kV/m and once to −100 kV/m.
31 Oct	8:04	25(R)	12, 23.5	E–W convergence line over Cape all morning. Electrified clouds moved onshore. E_Z ± 5 kV/m, and to +28 kV/m.
Layered clouds with westerly winds:				
1 Nov	14:10	2.5	13, 23.5	Thin cloud deck between 1 and 2.5 kft with cirrus above, no Cu, $|E_Z| < 200$ V/m.
4 Nov	7:13	layers	12, 23	Cloud layers with bases at 8, 11.5, and 18 kft and 1 to 2 kft thick, some rain showers. E_Z to −800 V/m at departure, then $E_Z < +500$ V/m.

vective cells. The third case was a complex situation with several decks of clouds. Field strengths at the ground exceeded 3 kV/m, but SPTVAR saw no field greater than 2 kV/m while flying over the surface mills at an altitude of 11,500 ft (3.5 km). This interesting example is treated as a special case study in Part II of this report.

On 30 September, SPTVAR flew through electrified clouds whose tops were reported to be around 35,000 ft (10.7 km). Several passes over Mosquito Lagoon were coordinated with lightning triggering attempts by William Jafferis of KSC. Lightning was not triggered.

On 26 September, SPTVAR flew through electrified clouds with lightning over the KSC field mill network. Electric field changes from lightning at SPTVAR and at the ground compare well in magnitude and sign. This technique can be refined and used in the future to calibrate airborne electric field measurements.

On 31 October, cloud tops were higher than the $-20\,°C$ level and the clouds were electrified but not producing lightning. Several regions of charge drifted west with the clouds. The regions of charge are well delineated in displays using barbs attached to the aircraft's track.

A number of days are discussed in more detail in Appendix D, as we mentioned above, and 4 November is discussed in detail in Part II of this report.

8 Conclusions

1. A real-time display of electric vectors attached to the track of the aircraft promises to be an invaluable aid for guiding the aircraft to regions of interest and for interpreting the results of the measurements. From these vectors the locations of regions of charge can be quickly identified. The display should be visible to controllers on the ground who guide the airplane and make decisions about electrical hazards to operations at KSC.

2. Airborne electric field measurements can be calibrated by comparing electric field changes at the ground with those at the airborne platform.

3. In ten flights into cumulus clouds whose tops were lower than the $0\,°C$ level, no significant electrification was encountered.

4. In the vicinity of electrified clouds, usually the electric field aloft is much greater than that at the ground, but we encountered one interesting exception in which the electric field at the aircraft's altitude of 11,500 ft (3.5 km) was lower than that at the ground.

5. On one occasion when there was a widespread cloud layer, the electric field disturbances coincided with embedded convective cells.

9 Recommendations

We recommend the following steps to enhance the value of airborne electric field measurements for routine use in determining hazards due to electrified clouds.

1. Continue to develop displays of the aircraft track and electric vectors as an aid to guiding the aircraft during operations and interpreting quickly the results of the measurements. Our present displays show only two of the three components of E simultaneously. Color displays have the potential of showing all three. The track of the aircraft with data should be displayed against a background of maps showing significant landmarks, boundaries of restricted areas, and radar echoes.

2. Develop methods for automatically deducing the location and magnitude of charges in clouds from aircraft measurements during the flight. When the electric field pattern measured at the aircraft is not too complex, it should be possible to find a simple model of charge to fit the measurements. The locations of the charges could be checked by new tracks in the vicinity of the charges.

3. Develop methods to estimate and display the reliability of aircraft measurements of electric vectors. The reliability is a function of the ratio of magnitude of the ambient electric field to the magnitude of the charge on the aircraft and the amount of charge released from the aircraft by corona discharges. Aircraft charging depends on the types and concentrations of particles impinging on the aircraft and the propulsion type (propeller, jet, or none) used by the aircraft.

4. Test the above techniques in field programs.

Since the number and types of clouds available to study during the 1988 field program were limited and since electrified clouds vary widely in anatomy and behavior, further field programs using airborne electrical measurements will be required. We specifically recommend the following.

1. Study the development of electrification in cumulus clouds as they ascend above the 0 °C level and as their tops descend back below 0 °C to determine what factors must be present for electrification to appear.

2. Study the variation of electric field strength with distance away from electrified cumulus clouds. Penetrate these clouds to ascertain the presence or absence of significant screening layers.

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3. Make airborne measurements around anvil clouds and other layered clouds to determine under what conditions they become electrified and to learn whether there are ever any cases in which the electrification cannot be identified by measurements of electric field at the ground.

4. Study clouds with rain whose tops are at any altitude below the -20 °C level to determine under what circumstances they might become electrified.

5. Airborne electrical measurements around winter frontal storms are either rare or non-existent. It is a good time to get a measurement program started.

We have two recommendations of a more general nature.

1. Aircraft measurements around electrified clouds would be greatly enhanced by data from a high resolution Doppler cloud physics radar located within the boundaries of KSC. We recommend now, as we have in the past, that KSC acquire such a radar with capabilities for vertical scanning. We also recommend that the aircraft display mentioned above be combined with the radar display to enhance the capabilities for real-time guidance of the aircraft.

2. An airborne electric field system with the capabilities we are developing will be a unique state-of-the-art facility for characterizing electrified clouds. While we have stressed the importance of real-time techniques for interpreting the data, much of the value in the data will appear only in later analysis when they are viewed in the context of other information about the clouds. Thus we recommend that all the electric field and cloud physics data collected by the airborne field mill system be available to a broad scientific community and that strong liaisons be developed with some investigators for the purpose of promoting the understanding of electrified clouds.

10 Acknowledgments

11   References

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Jones, J. J., 1988: Electric charge acquired by airplanes penetrating thunderstorms, *Proc. 8th Int. Conf. on Atmos. Elec.*, Uppsala, Sweden, 560–565.

Marshall, T. C., W. D. Rust, W. P. Winn, and K. E. Gilbert, 1989: Electrical structure in two thunderstorm anvil clouds, *J. Geophys. Res. 94*(D2), 2171–2181.

A   Field Mill Calibrations

Calibrations of the SPTVAR field mills were conducted three times at Patrick AFB during the airborne field mill project from September to November 1988. The calibrations were conducted with the field mills installed on SPTVAR and the data were collected through SPTVAR telemetry and recorded in the SPTVAR ground station just as if the airplane were in flight and measuring atmospheric electric fields. The calibrations were done using a special calibration jig consisting of a metal can which was slipped over the cylindrical mill housing. The can was a snug fit to the mill and had a stainless steel plate parallel to its bottom which was mounted on a Teflon insulator so that a test voltage could be applied to it while it was held a fixed short distance from, and parallel to, the face of the field mill. A series of test voltages was then applied between the test plate and the can and thereby the mill housing. The first calibration in Florida was carried out on 22 September 1988. The test voltages were supplied by a battery pack that provided eight test voltages plus a zero volt setting which shorted the insulated plate to the can of the calibration jig. By reversing the polarity of the battery pack an additional eight negative voltages could be applied to the calibration jig. In this way 17 voltages between -178 V and $+178$ V were used for the mill calibrations.

The first step in the calibration of the mills was to measure the battery pack voltages with a digital voltmeter. This was done with the telemetry transmitter turned off since, when on, the radio frequency energy from the transmitter corrupts the digital voltmeter readings. Then the telemetry was turned on and data recording initiated in the SPTVAR ground station. A full sequence of test voltages was then applied with the calibration jig fitted to the top mill, beginning with $+178$ V and continuing to -178 V. Each voltage was applied for five seconds except for the zero voltage which was applied for ten seconds to allow for polarity reversal (interchange of the two wires from the battery pack). This procedure was repeated for the bottom, port, starboard and aft mills in that order.

The second and third calibrations in Florida were carried out on 17 October and 11 November 1988. For these calibrations a second battery pack with five voltages between zero and 1,160 V was available. A sequence of voltages was applied using the low-voltage battery pack followed by a second sequence using the high-voltage battery pack. In each case the sequence included applied voltages ranging from the most positive to the most negative by means of a polarity reversal in the zero applied voltage step. Once again each test voltage was applied for five seconds, except the zero voltage step at the mid point which was held for ten seconds as on 22 September.

The digital data tape was analyzed to determine the response of each field mill to the electric fields applied with the calibration jig. For each sensitivity signal of each mill the mean of the digital numbers representing the field mill response was calculated for each

applied field in the calibration sequence. This mean value was then converted back into the corresponding mill voltage. The results of the calibrations are as follows:

Noise level: From plots of the raw digitized mill signal voltages the noise level of the field mills was found to be typically ± 1 digitization step, or about ± 5 mV.

Field mill response: A working value of the electric field at the face of each mill was calculated from the applied test voltage divided by the 1.54 cm spacing between the charged plate in the calibration jig and the front surface of the rotating shutter of the mills. A straight line was then fitted to the mill voltages, V_j (recovered from the mean digital telemetry numbers), as a function of the calibration jig electric fields, E, according to the equation

$$V_j = a_j E + V_{j0}. \tag{A1}$$

In (A1), $j = T, B, P, S,$ or A and indicates the top, bottom, port, starboard or aft mounted field mill; V_{j0} is the output voltage of mill j when $E = 0$; and a_j is the gain of mill j in units of V/kVm^{-1}. Figure 10 shows a plot of the measured mill voltage as a function of E (the $+$ symbols) for the medium sensitivity signal from the bottom mill. The straight line is the best fit to the data determined according to (A1). The data shown in Fig. 10 are typical of all three sensitivities and all five mills.

Linearity of mill response: In order to further investigate the linearity of the field mill responses a plot was also made of the difference between the measured mill voltage, V_j, less the mill voltage predicted from (A1) for each calibration step. Typically the largest difference is less than or of the same size as the least count voltage of 5 mV for the analog to digital converter in the data encoder/telemetry system on board SPTVAR.

Comparison of calibrations: The values of the mill gains, a_j in (A1), determined in the three mill calibrations using the low-voltage battery pack were found to be within 1% of each other, as were the two calibrations using the high-voltage battery pack. However, the gains determined using the high-voltage battery pack were 2 to 3% larger than the gains determined using the low-voltage battery pack. Edge effects in the calibration jig are probably responsible for this difference. We have chosen to use the mill gains determined from the high-voltage battery calibrations since they cover a larger portion of the usable signal range of the mills.

Solving (A1) for E allows for the determination of the fields at each of the mills from

$$E_j = a_j^{-1}(V_j - V_{0j}), \tag{A2}$$

where values of a_j^{-1} determined by the calibrations are listed in Table 4.

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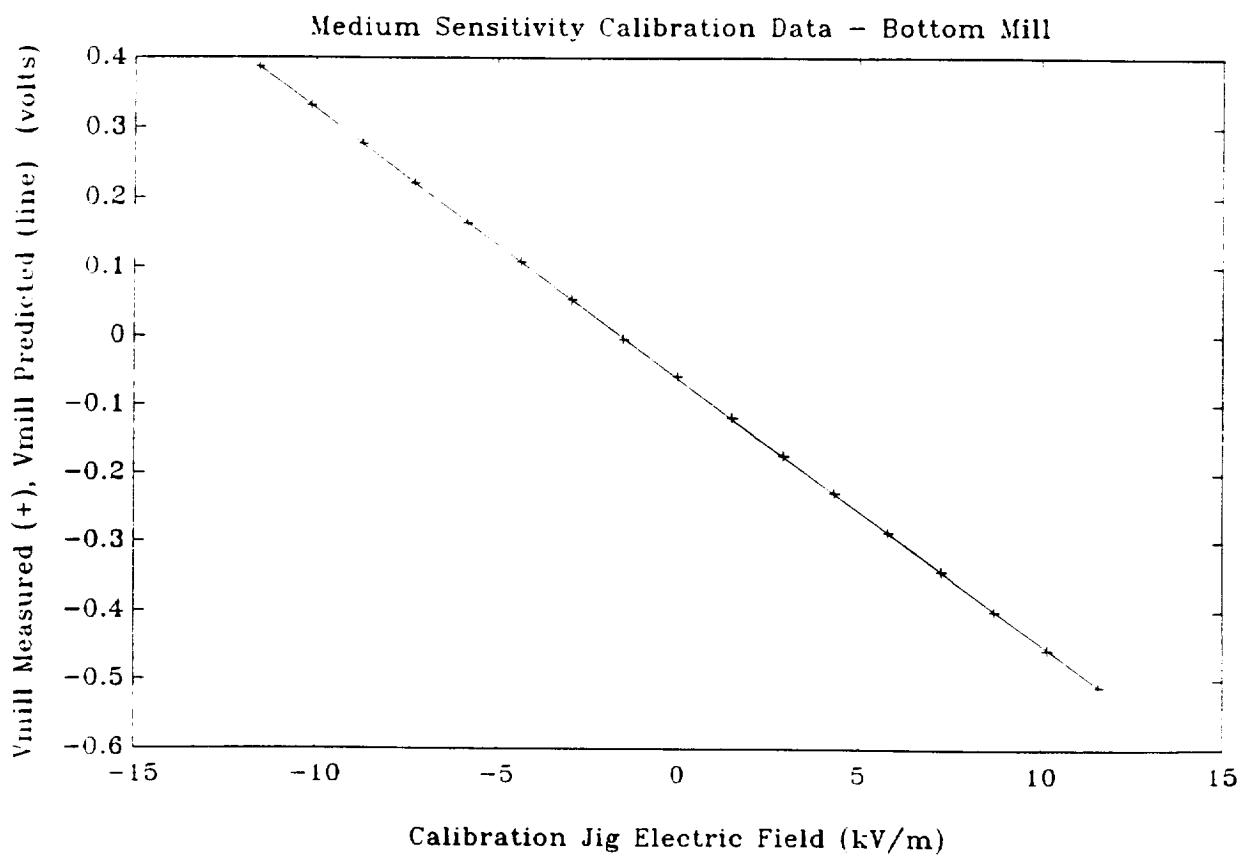
Figure 10: Calibration curve, bottom mill, medium sensitivity signal. The measured mill voltages are shown by the + symbols. The straight line is the best fit to the data determined according to Equation (A1).

Table 4:

CALIBRATION COEFFICIENTS
SPTVAR FIELD MILLS
SPTVAR Operations, KSC - Patrick AFB, 1988
Values of a_j^{-1}, in $E = (a_j^{-1})(V_j - V_{0j})$, in $kVm^{-1}/Volt$

	Mill	j	a_j^{-1}
Low Sensitivity Signal	top	T	−175.
	bot	B	−177.
	port	P	−172.
	stbd	S	−168.
	aft	A	−165.
Medium Sensitivity Signal	top	T	−25.0
	bot	B	−25.3
	port	P	−24.9
	stbd	S	−24.1
	aft	A	−23.3
High Sensitivity Signal	top	T	−2.56
	bot	B	−2.42
	port	P	−2.71
	stbd	S	−2.63
	aft	A	−2.57

B $\vec{E}$ Component Determination

The method for finding the ambient $\vec{E}$ components from the fields at the individual mills, briefly outlined in Jones (1988) and Dye *et al.* (1988), utilizes the following relationships:

$$E_Z = (1/2)(E_T - R_Z E_B)C_Z, \tag{B1}$$

$$E_Y = (1/2)(E_P - R_Y E_S)C_Y, \tag{B2}$$

$$E_{X(Z)} = -(E_A - R_{XZ}E_{Q(Z)})C_{XZ} \tag{B3}$$

$$\text{and} \quad E_{X(Y)} = -(E_A - R_{XY}E_{Q(Y)})C_{XY}. \tag{B4}$$

where

$$E_{Q(Z)} = (1/2)(E_T + E_B) \tag{B5}$$

$$\text{and} \quad E_{Q(Y)} = (1/2)(E_P + E_S). \tag{B6}$$

B.1   Charge subtraction

The charge subtraction coefficients, R in (B1)–(B4), are determined with the aid of artificial chargings of SPTVAR in a weak fair-weather field environment. While operating from Patrick AFB during fall 1988, SPTVAR was artificially charged 26 times using a 5 kV voltage supply. At least one charging was conducted on all but four of the 20 flights. Using the data from a selected set of these chargings, the charge subtraction coefficients listed in Table 5 have been determined so that the deduced E_Z, E_Y and E_X of (B1)–(B4) are substantially independent of the airplane charge, Q.

B.2   Form factor determination

The C coefficients are the form factors which correct for the distortion and enhancement of the ambient $\vec{E}$ at the mill sites by the airplane geometry. They are listed in Table 5.

The ratio C_Y/C_Z for SPTVAR has been checked with the aid of data obtained during roll maneuvers of the airplane when a quasi steady field was present while the airplane was flying out of cloud and under an anvil cloud on 27 September (88271). The method used is outlined in Dye *et al.* (1988).

A similar procedure using up and down pitching of SPTVAR under similar ambient field conditions was used to check the ratio C_X/C_Z.

The overall form factor, C_Z, was extrapolated from the value determined in 1986 when SPTVAR, with its original mills, was flown repeatedly past a tethered, balloon-borne E

Table 5:

CHARGE SUBTRACTION COEFFICIENTS
AND
FORM FACTORS
ONR/NMIMT SPTVAR Airplane
SPTVAR Operations, KSC - Patrick AFB, 1988

Sensitivity	R_Z	R_Y	R_{XZ}	R_{XY}
Low	1.12	0.97	2.38	2.20
Medium	1.10	1.00	2.42	2.27
High	1.08	1.00	2.42	2.26

Sensitivity	C_Z	C_Y	C_{XZ}	C_{XY}
All	0.18	0.29	0.06	0.05

field meter in the presence of an ambient field. (Such an opportunity did not occur during the operations at Patrick AFB since no balloon-borne electric field meters were available at KSC during the period of the SPTVAR flights.) The ambient field during the 1986 measurements was predominantly vertical and E_Z measured by the balloon mill varied between 5.0 and 6.4 kV/m. The uncertainty of the balloon mill measurement of E_Z was about ± 10%. Since the precision of the SPTVAR measurement of E_Z during these 1986 measurements was ± 1%, the mean value of C_Z determined in 1986 has about the same ± 10% uncertainty as the balloon mill E_Z measurement. A single fly-by of a free balloon-born E mill in 1984 yielded a value of C_Z 5% smaller than the 1986 value.

On 26 September we gathered data for a new method for calibrating airborne electric field instruments. This method, which compares electric field *changes* at the aircraft and at the ground, is discussed in Appendix D, Section D.4.1.

For SPTVAR and its mill configuration, the deduced E_Z, E_Y and E_X from (B1)–(B4) usually are good measures of the components of $\vec{E}$, provided that the proper values of the charge subtraction coefficients and form factors are determined. Although $E_{Q(Z)}$ and $E_{Q(Y)}$ are primarily determined by the net airplane charge Q, they have a significant dependence on the atmospheric E_X. The result is that the correct values of C_{XZ} and C_{XY} are somewhat reduced from what would be necessary if the $E_{Q(Z)}$ and $E_{Q(Y)}$ did not contribute to the dependence of the deduced $E_{X(Z)}$ and $E_{X(Y)}$ on the atmospheric E_X.

C Track-plotting Program "SPT"

The program SPT, which runs on an IBM PC or compatible computer, displays data along the track of the aircraft along with boundaries of aircraft restricted areas and locations of surface field mills. The data on which SPT operates are an abbreviated serial stream supplied by the main data recording computer at a rate of about 0.4 Hz, the rate at which the Loran data updates. SPT operates in two modes: a record mode for use during flight and a playback mode for use post-flight.

The record mode is obtained by execution of SPT without specifying any options. The program draws the screen and then starts plotting the SPTVAR ground track while sending the received data to a modem, to a parallel printer and to a file on the hard disk. The following are featured in the console display:

- magnetic north lines at 5 nmi intervals east and west of field mill #12 (PAFB runway intersection).

- KSC field mill numbers.

- one-minute time ticks on the SPTVAR track.

- circles of radius 2 statute mi (R2931 boundary) and 3 nmi around Aerostat mooring.

- boundaries of aircraft restricted areas R2933 and R2934.

The playback mode requires a filename parameter and any option parameters. The program reads the named file, draws the screen, and traces the airplane track.

In the playback mode SPT can be run with a number of options.

-r Display range rings at increments of 5 nmi from PAFB.
-l suppress display of KSC field mill numbers.
-t suppress time ticks on the track every minute
      (automatic for -4 and -5 options).
-o Set the display to 30 x 50 nmi with PAFB at the bottom
      (default is 20 × 33 nmi with with center near mill #26).
-4 Plot E_Z data: E_Z is shown as a bar graph horizontally from the track
      at each data position with positive E_Z to the right.
-5 Plot E_Y data: As above. Sign convention is that positive
      E_Y plots to port (left) side of airplane.

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While the program SPT is executing in either mode, the following options can be activated by pushing a single "hot" key.

Esc   Ends the program.

Spacebar   Displays the latest data line at the bottom of the screen:
           In Record mode: the plotting continues.
           In Playback mode: the plot halts until the Spacebar is pressed again.
           While halted, the screen can be printed one or more times with the
           "p" key, and the other hot keys also work.

p   Prints the screen, on the printer, if the plot has been halted due to
           Spacebar having been pressed.

t   Prints a label for the most recent time tick in hhmm Z.

c   Clears the screen for a clean start for a new track.

n   n(orth), also s(outh), e(ast), or w(est): moves the window on the
           screen in the given direction (in 5-minute steps of latitude or longi-
           tude) to help center the track. The previous track is erased.

D Individual Flight Summaries

In this appendix the indented portions of the discussions which give a weather synopsis are condensations of daily synoptic summaries prepared by Ms. Launa Maier of KSC. Notice that the KSC field mill network contour plots, and thus Ms. Maier's discussion, follow the potential gradient convention for the sign of the electric field: $\nabla V = -E$ is positive when positive charge overhead dominates. We shall use the opposite convention, that E is positive when it exerts an upward force on a positive charge (i.e., when negative charge overhead dominates) for all SPTVAR data. Most of the flight track plots presented in this appendix were made by the program SPT with the E_z barb option selected. The threshold for the barbs was usually $|E_z(\text{lowsensitivity})| = 1$ kV/m. In these flight track plots, the barbs representing positive E_z are drawn toward the right of the figures.

D.1 Morning cumuli associated with convergence.

The flights of 30 September, and 5, 14 and 16 October 1988 were conducted with the objective of studying morning clouds which were associated with zones of convergence. The local (EST) take-off times were 8:58, 9:54, 7:26 and 6:46 AM respectively.

D.1.1 Summary: 30 September 1988 (88274)

> On 30 September the GOES IR image for 07 Z showed a NW-SE convergent line off the northeast coast of Florida, stretching from just west of Jacksonville, Florida, to about 75 km offshore of CCAFS. By 13 Z the convergent line was approximately 120 km wide and moving gradually westward, with clouds over the northern part of KSC. In the vicinity of the Cape, clouds with the maximum echo tops were approximately 30 km offshore and the tops declined in altitude as the clouds moved inland. The morning CCAFS sounding revealed easterly surface winds that shifted to east-southeasterly through 29,000 ft (8.8 km). Above that height the winds backed (counterclockwise) with height, shifting from southeasterly to northwesterly at 46,000 ft (14 km). The local atmosphere was moist below 6,000 ft (1.8 km) and dry above 21,000 ft (6.4 km). [Skew T diagrams for the 12 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 11.]

SPTVAR flew from 1358 to 1658 Z with the objective of investigating clouds over the northern part of the KSC area that were part of the cloud band noted above. The interesting part of the flight track for this day is shown with horizontal E_z barbs in Fig. 12. The airplane climbed to 6,000 ft (1.8 km) altitude and flew directly to a cloud that covered

35
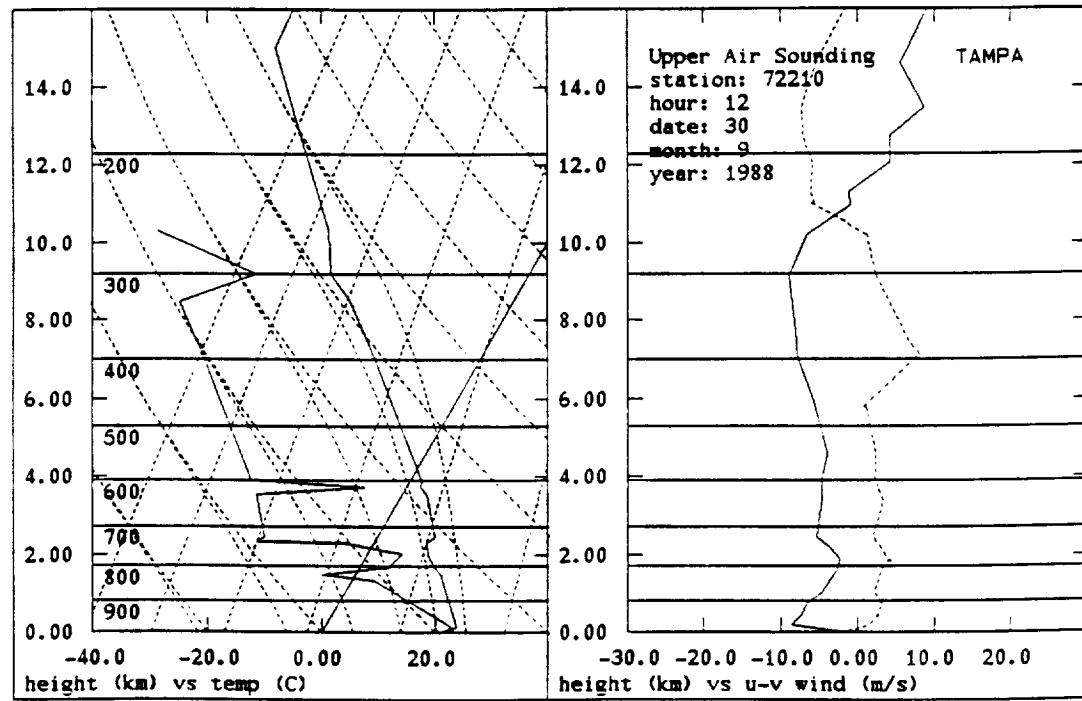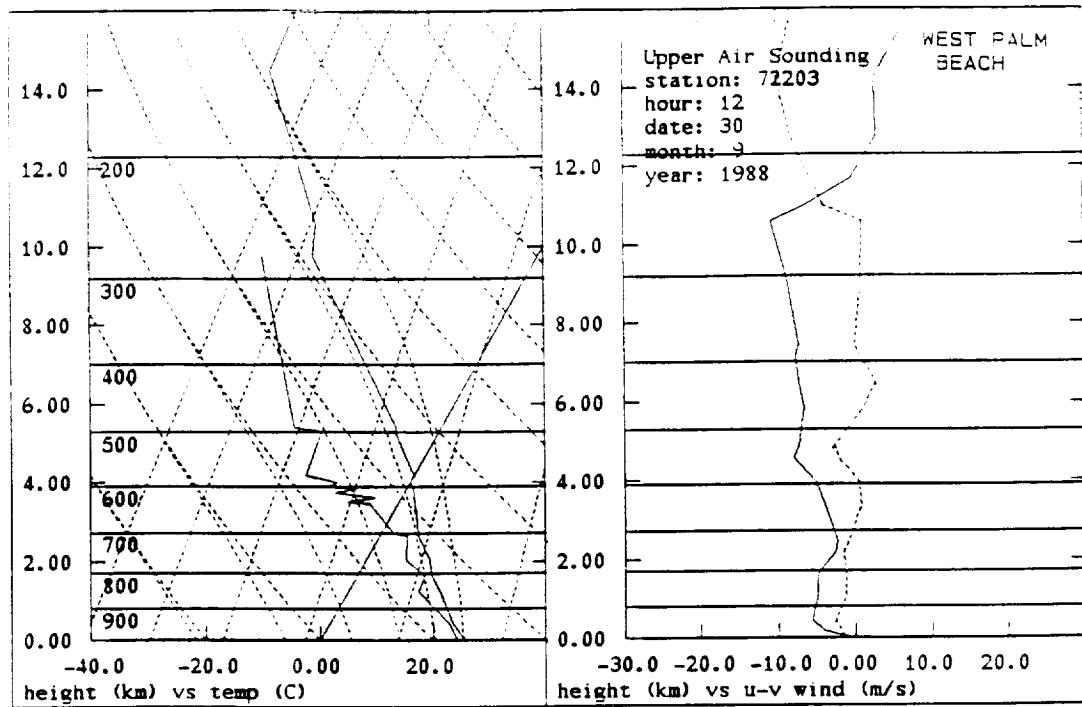
Figure 11: Skew T diagrams for the 12 Z West Palm Beach (A) and Tampa, Florida, (B) soundings on 30 September 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

all of Mosquito Lagoon. SPTVAR flew into this cloud and measured E_z up to $+14$ kV/m at 1430 Z when offshore the center of Mosquito Lagoon. SPTVAR immediately reversed course and saw E_z up to $+5$ kV/m as it returned through this cloud. The electrified part of this cloud was so far north that it was abandoned; SPTVAR returned to the KSC area.

By 1500 Z the cloud over Mosquito Lagoon had dissipated but a new one was developing over the northwest part of Merritt Island and the southern part of the Lagoon. While in this cloud at 12,000 ft (3.7 km) altitude, SPTVAR measured E_z values of $+1$ to 2 kV/m between mills #6 and #10 at about 1515 Z and near mill #2 at 1517 Z (see Fig. 13). SPTVAR flew on until just offshore of Mosquito Lagoon and reversed course at 1522 Z in a region of clear air. At 1520:23, before SPTVAR made this course reversal, a wire-trailing rocket was fired from the rocket-triggered lightning site ('J site' in Fig. 13). Although lightning was not triggered, there was an apparent field change observed at the rocket site, but not at mill #2. SPTVAR was too far away to have been able to measure the cloud electric field at this time.

Returning southward, SPTVAR penetrated the cloud again and passed 0.5 km east of the rocket-triggered lightning site at 1526:40 Z. It passed east of mill #2 at 1527:27 Z and directly over mill #5 at 1528:36 Z. The flight track for this penetration is shown in Fig. 14 with E_z barbs plotted along the track line. The McGill radar echo-top display showing the cloud at 1514 Z is reproduced in Fig. 15. From about 4 km north to about 4 km south of mill #2, SPTVAR measured positive E_z and negative E_Y. E_X measured by SPTVAR was positive north of the rocket site and negative south of mill #2. E_z reached about $+15$ kV/m and E_Y about -5 kV/m in the vicinity of the rocket site and mill #2, with a strong local peak of 26.5 kV/m in E_z when SPTVAR was between the rocket site and mill #2. The magnitudes and polarities of the electric field components indicate that there was a negative charge overhead and to the right (west) of the airplane in the direction of the main part of the cloud. Detailed plots of E_Y and E_z measured by SPTVAR during this penetration are shown in Fig. 16. The times identified by the letters a, b and d in Fig. 16 are the times that SPTVAR passed the rocket site, mill #2 and mill #5 respectively.

A second wire-trailing rocket was launched at 1527:58 Z, when SPTVAR was about 3.8 km south-southeast of the rocket launch site. Again there was a discernible field change at the rocket launch site, but none in the recorded mill #2 signal. The rocket launch time is identified by the arrow labeled c in Fig. 16. There does not appear to be any significant change in E_z at the time of the rocket launch. Unfortunately, E_Y is very noisy from 1527 to 1528:37 Z (15.45 to 15.47 Z in Fig. 16 whose time axis is labeled in decimal hours) due to corona emission resulting from strong LWC induced charging of the airplane. For both rocket launches, ∇V at the launch site decreased to near zero in about six seconds and then recovered to its pre-launch magnitude in about 20 to 30 seconds. These declines in the potential gradient may be due to the ascending rocket carrying the Earth's potential high above the field meter at the launch site. The strong E_Y component measured by
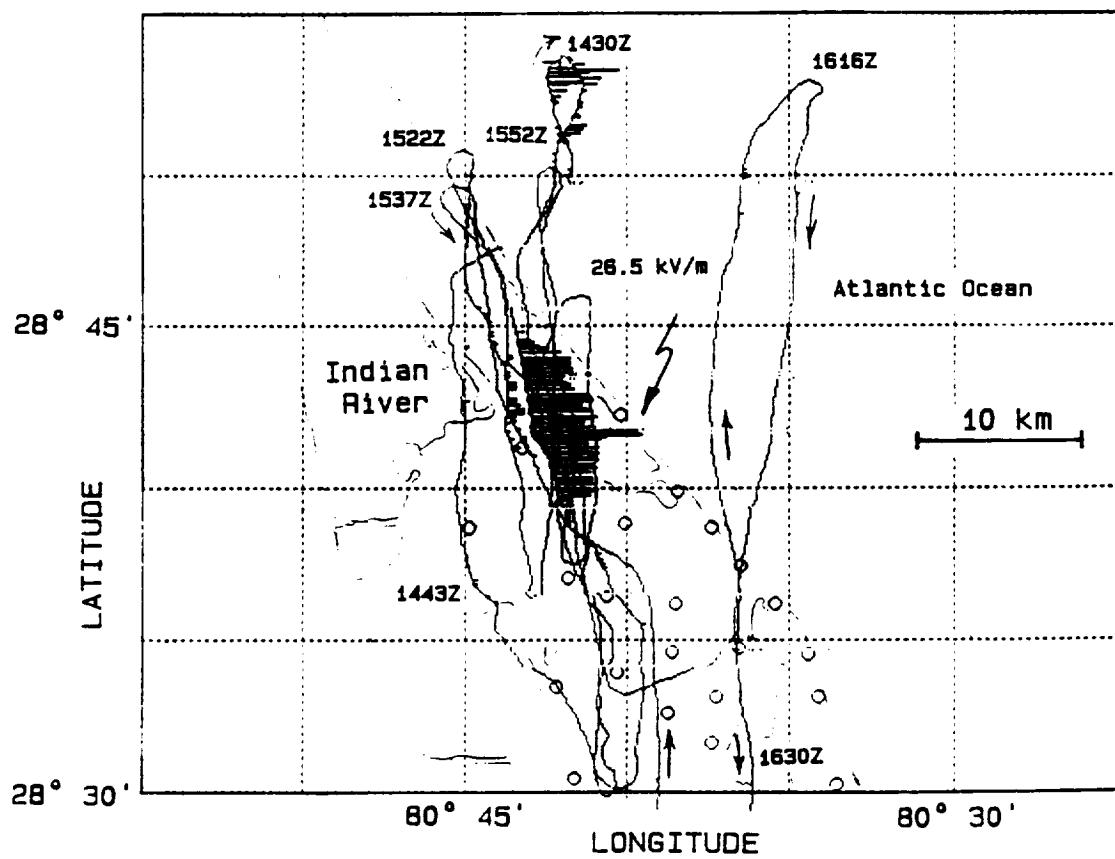
Figure 12: Part of the 30 September 1988 SPTVAR flight track with E_Z barbs along the track. Positive E_Z is plotted toward the right side of the figure. A barb 1 mm long represents $E_Z = 2$ kV/m.
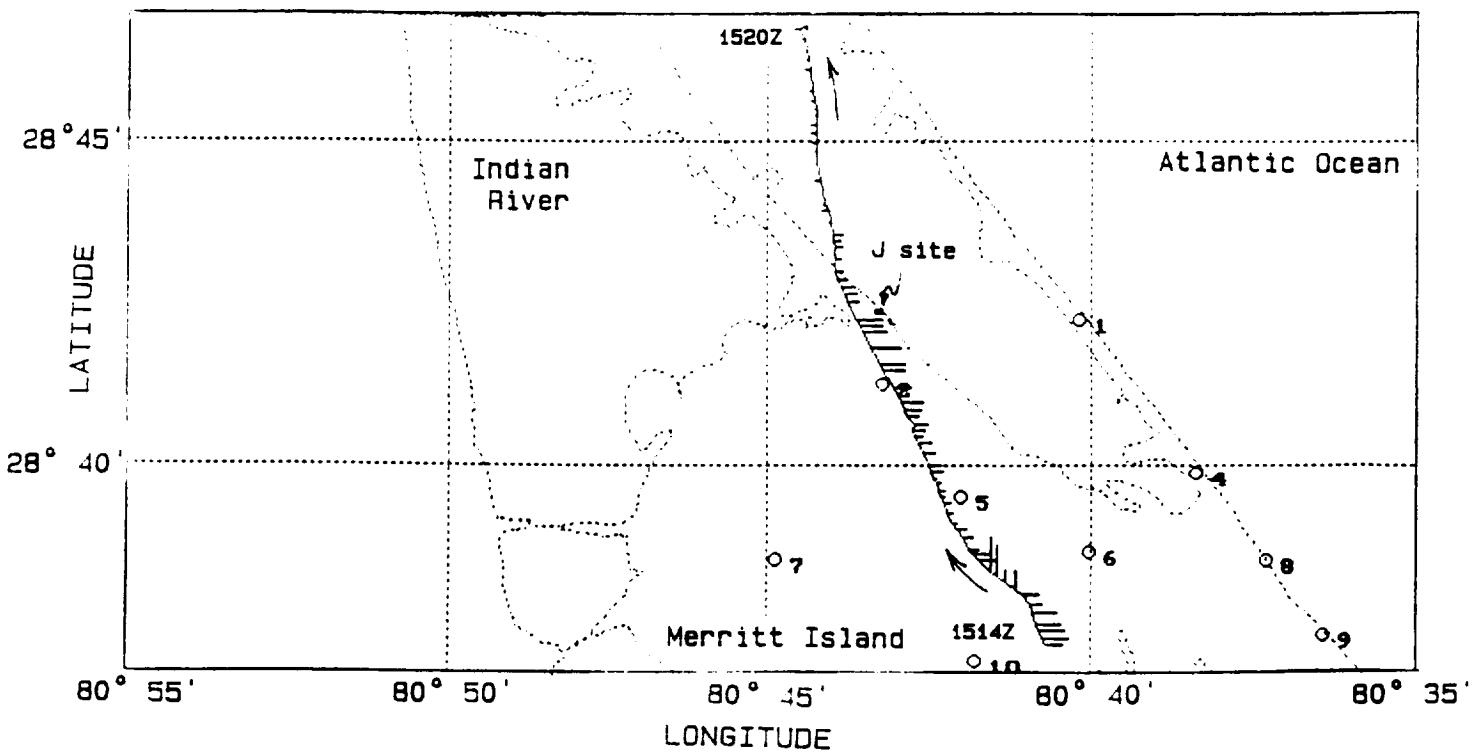
Figure 13: The 30 September SPTVAR flight track between 1514 and 1520 Z with E_Z barbs plotted along the track. Positive E_Z is plotted toward the right side of the figure. A barb 10 mm long represents $E_Z = 3.8$ kV/m.
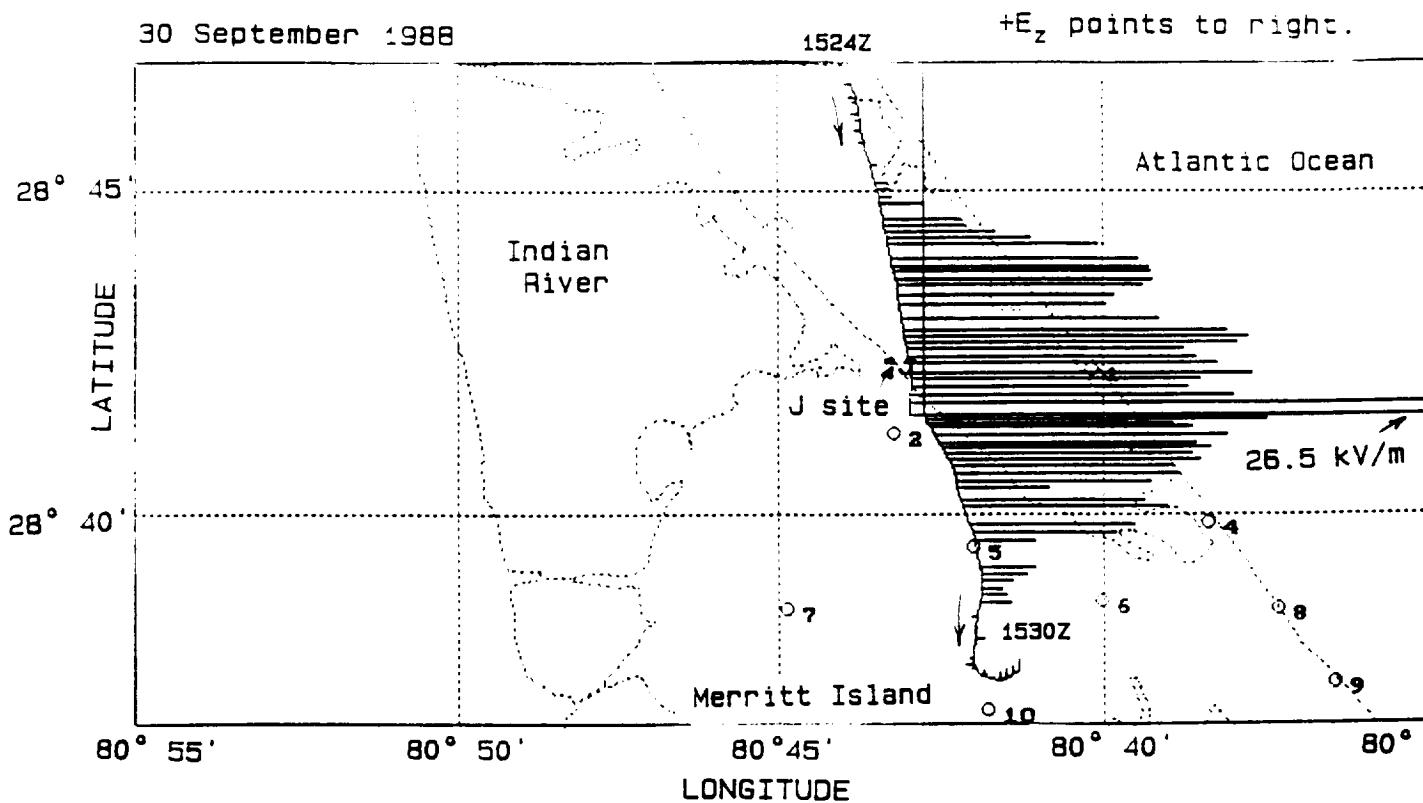
Figure 14: The 30 September SPTVAR flight track with E_Z barbs between 1524 and 1530 Z. The barb scale is the same as in Fig. 13. Note the large increase in the electric field over that encountered on the previous north-bound flight segment.
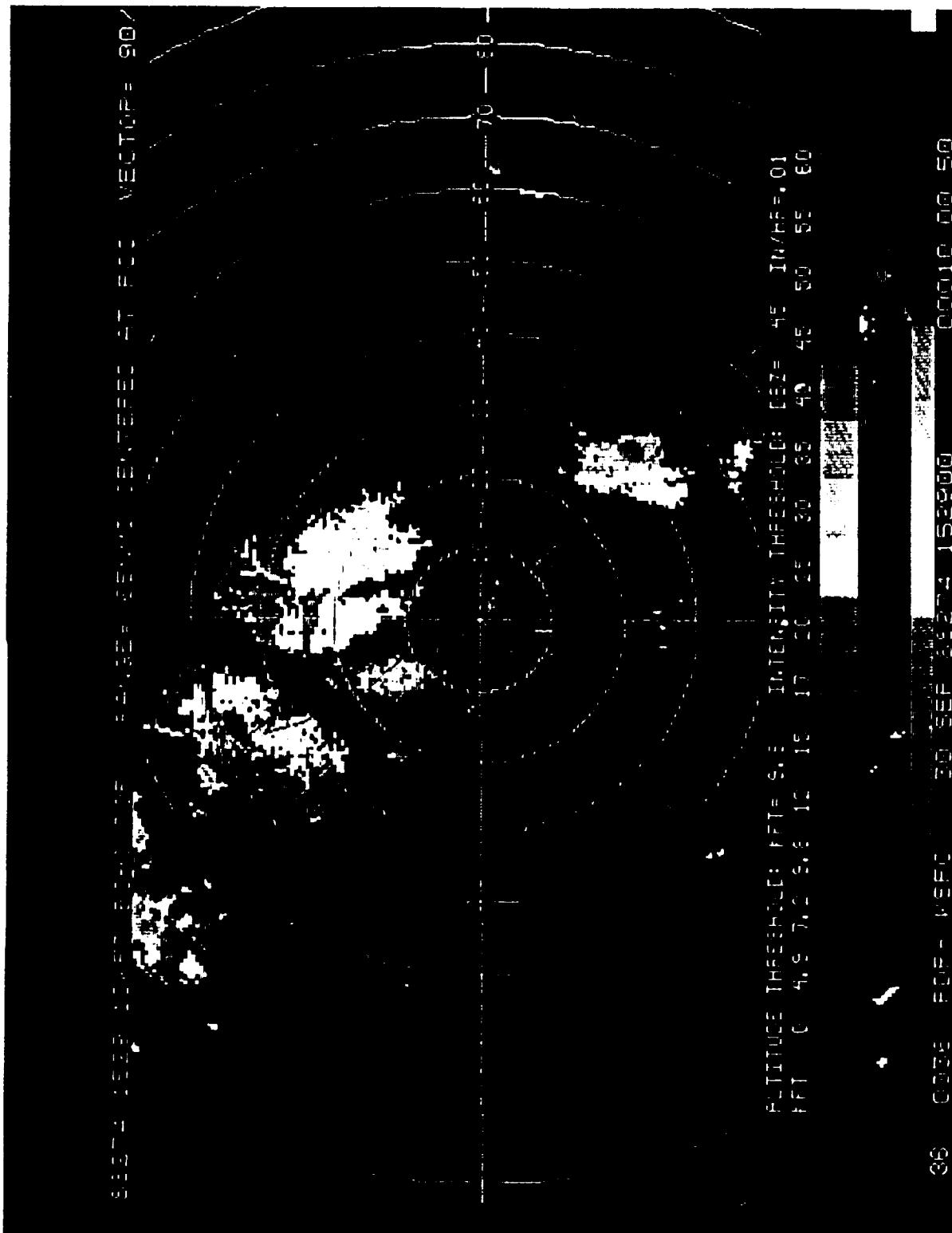
Figure 15: The McGill radar echo top display for 1529 Z on 30 September 1988. The cloud over the triggered lightning rocket site is the small one at about 330 degrees and 10 to 18 km from the center of the display, which is coincident with the Range Control Center at CCAFS.
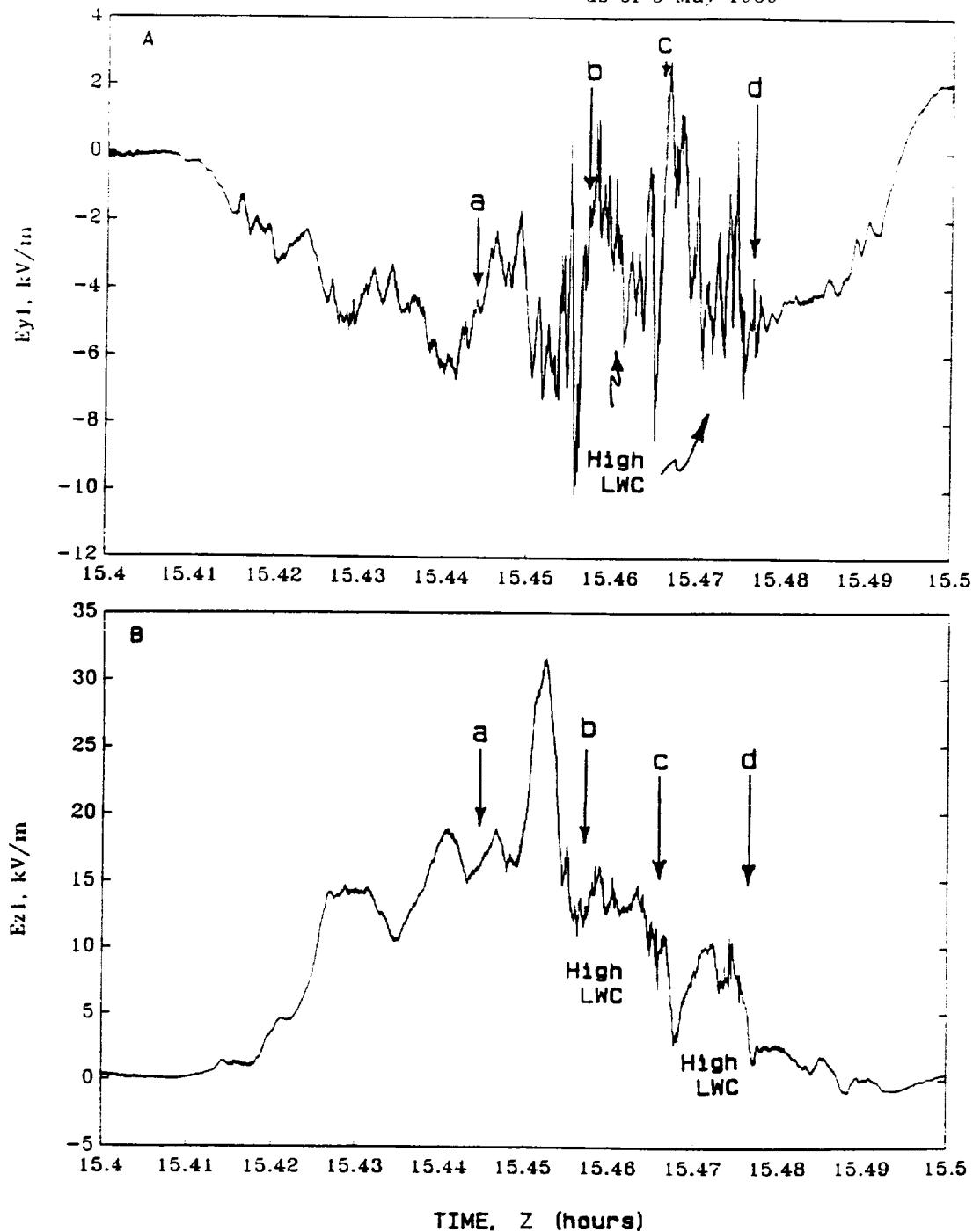
Figure 16: E_Y (A) and E_Z (B), medium sensitivity, from 1524 to 1530 Z on 30 September 1988. SPTVAR, headed south, passed east of the triggered lightning site and field mills #2 and #4 at the times identified by the letters **a**, **b**, and **d**. The letter **c** identifies the launch time of the second wire-trailing rocket fired in an unsuccessful attempt to trigger lightning.

SPTVAR when it passed almost over the rocket site suggests that the rocket may have been displaced too far horizontally from the main charged region of the cloud for it to have had a high probability for triggering a lightning discharge. Indeed, data from the KSC ground-based field mill network indicate that the main cloud charge was centered southwest from the launch site and somewhere near the north end of the SLF.

Electric field values measured by selected ground-based field mills at the times of the wire-trailing rocket launches and by SPTVAR at the time of the second launch are presented in Table 6.

At the time of the second rocket launching, the cloud electrification was apparently near maximum, since when SPTVAR passed the rocket launch site north-bound at 1532:40 and again south-bound at 1542:40 Z only a small electric field was measured (Fig. 17). By this time the McGill radar echo-top display showed the east edge of the cloud over the rocket launch site. On the next north-bound and south-bound passes, 1549:50 and 1558:20 Z, the cloud had moved farther west and no electric field was measured. Thereafter SPTVAR flew after a cloud over the ocean well offshore of Mosquito Lagoon, and then returned to PAFB.

At 1528:36 Z when SPTVAR passed directly over mill #5 at about 12,000 ft (3.7 km), E_z was about 2.6 kV/m. At this time mill #5 reported $\nabla V = -2.04$ kV/m, so the field strength at 12,000 ft (3.7 km) was similar to that at the surface.

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Table 6:

ELECTRIC FIELDS AT LAUNCH OF WIRE-TRAILING ROCKETS
30 SEPTEMBER 1988

All electric field values are in kilovolts per meter.

KSC Mill Number*	First Rocket Launch 1520:23 Z	Second Rocket Launch 1527:58 Z	Field Value Uncertainty
J	3.2	4.0	±0.4
2	2.9	3.8	±0.4
5	3.3	2.6	±0.4
6	2.0	2.1	±0.4
7	2.2	0.0	±0.4
4	0.4	0.6	±0.4
SPTVAR (E_z)	—	11.5	±0.5

*The KSC field mills are listed in order of increasing distance from the wire-trailing rocket launch site, **J**.
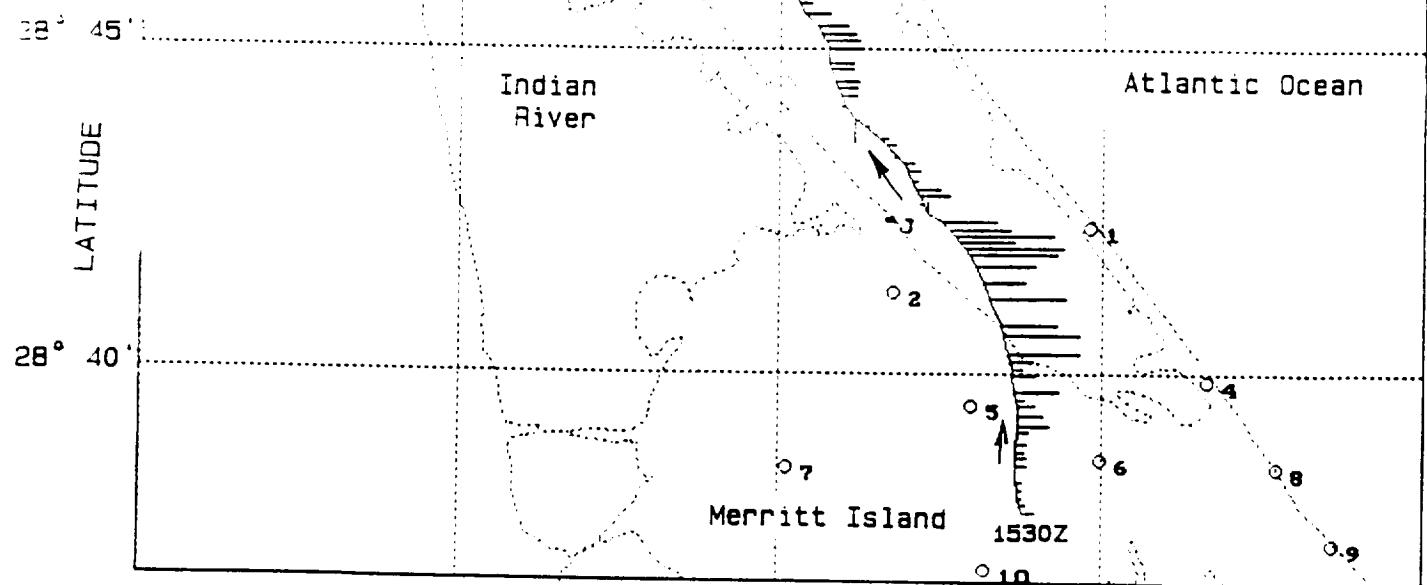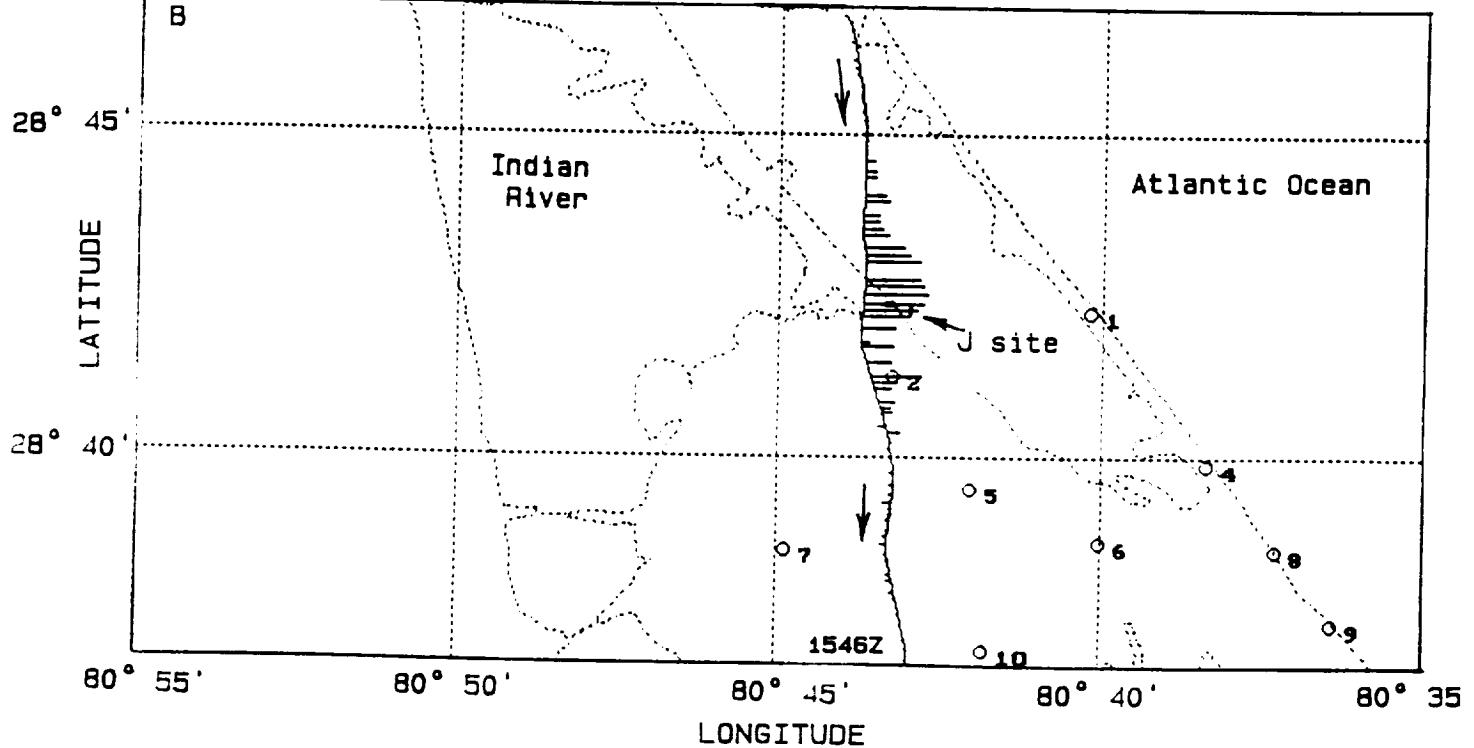
Figure 17: The SPTVAR ground track and E_Z for (A) north- and (B) south-bound flight legs passing the rocket-triggered lightning site at 1532:40 and 1542:40 Z. The electric field is greatly diminished from that encountered on the previous pass.

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D.1.2 Summary: 5 October 1988 (88279)

Convection formed along an east-west convergence line through Tampa and CCAFS that was related to a stationary east-west front in southern Florida. The convergence line was evident on the satellite imagery as cloud masses off both coasts of Florida, near Tampa and CCAFS. The CCAFS sounding revealed moist air up to 9,000 ft (2.7 km) and extremely dry air above 10,000 ft (3 km). The winds were northeasterly from the surface to 6,000 ft (1.8 km) and westerly to southwesterly above. Convection formed all day along the convergence line offshore. The low level clouds moved slowly toward the southwest into the CCAFS area. The mid-level clouds moved from the west toward the east-northeast. Very little convection was present inland. [Skew T diagrams for the 13 Z West Palm Beach and 12 Z Tampa soundings are shown in Fig. 18.]

The objective of this mission was to study cumulus clouds growing below an altocumulus deck. SPTVAR took off at 1454 Z and during the earlier part of the flight flew at 6,000 ft (1.8 km) altitude. During this time it made very few cloud penetrations. After arriving over KSC, SPTVAR was requested to fly over mills #4 and #6 which had both been reading a few hundred V/m negative (since at least 1215 Z, according to the KSC electric field contour plot displays). SPTVAR made various passes over mill #4 and near #6 but saw no electric field anywhere. Later a technician visited the mill sites and, finding that they were not rotating, he restarted them. At 1640 Z SPTVAR began climbing, and after 1653 Z it flew at 12,000 ft (3.7 km). The SPTVAR flight track is shown in Fig. 19.
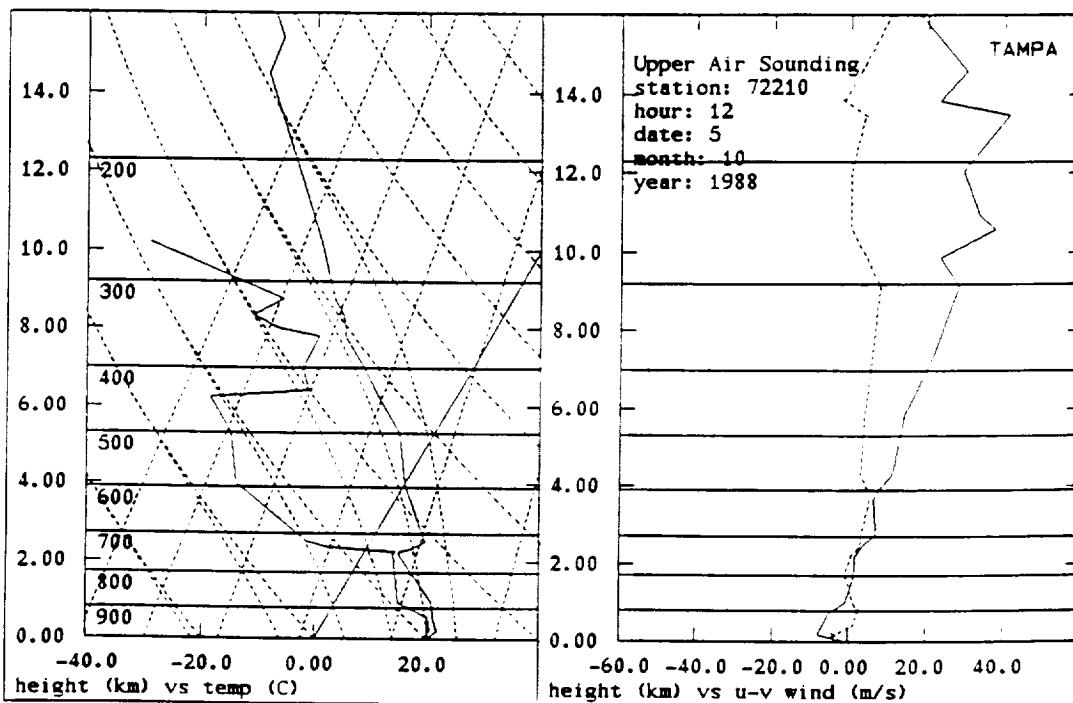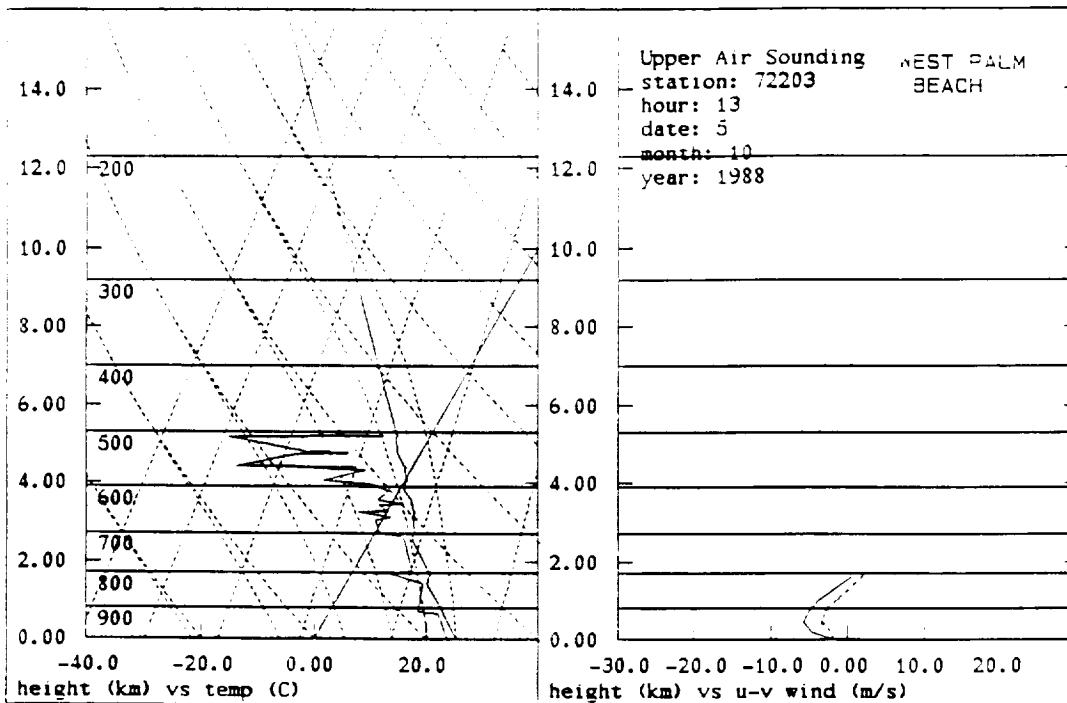
Figure 18: Skew T diagrams for the 13 Z West Palm Beach (A) and 12 Z Tampa, Florida, (B) soundings on 5 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

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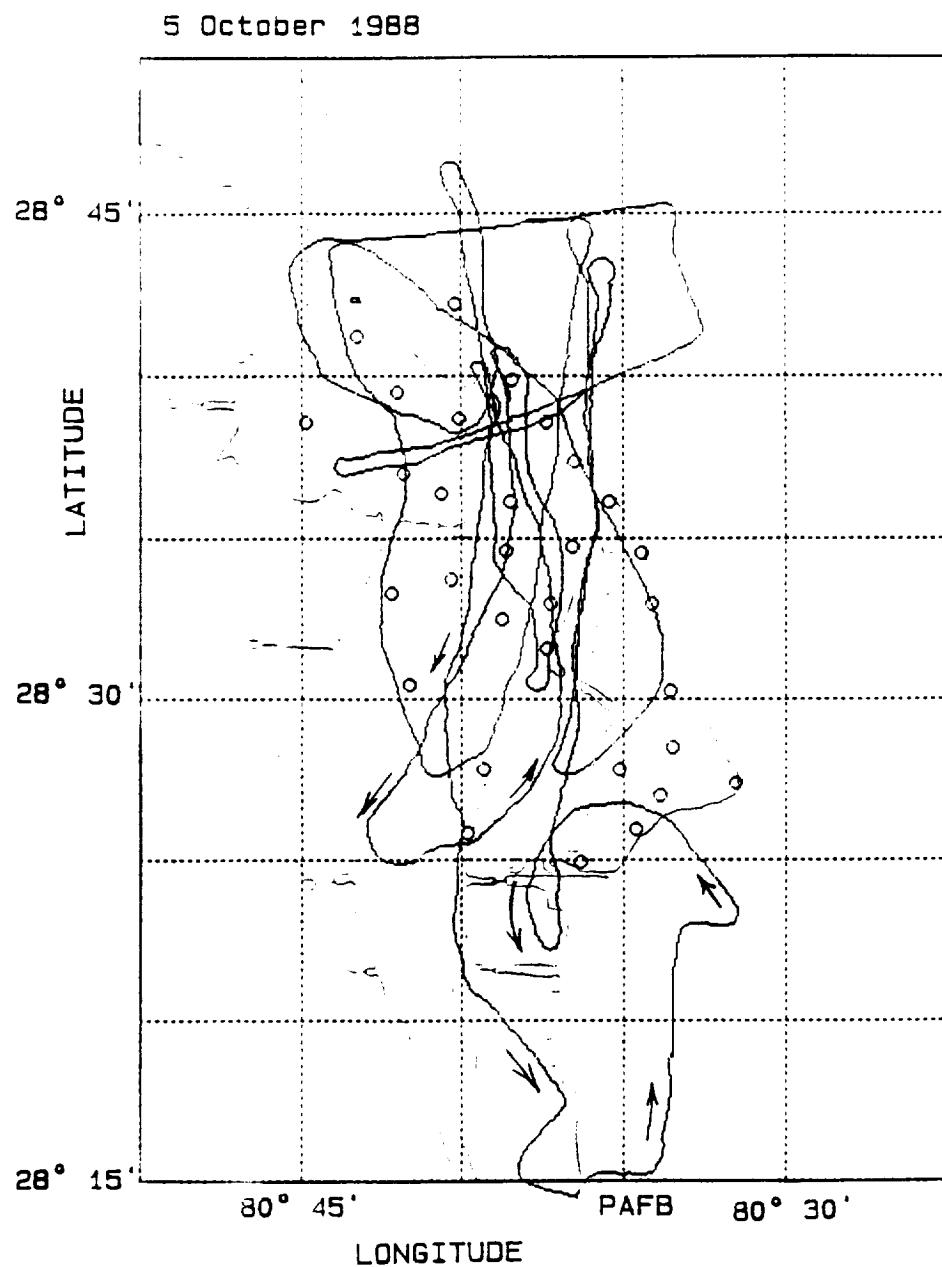
Figure 19: The 5 October 1988 SPTVAR flight track with the E_Z barb option selected. The lack of barbs along the track indicates $|E_Z| < 1$ kV/m for the entire flight.

During this flight Ms. Launa Maier compared aircraft positions with the radar data displayed on the McGill terminal. The resolution of the data on the terminal was better than the resolution of the Echo top charts printed on 5 October. Aircraft and cloud top locations were estimated and plotted on these radar charts with descriptive notes written at the bottom of each chart. The following discussion is based on these records.

At 1659 Z the radar top of one cell exceeded 25,000 ft (7.6 km). This occurred over Banana Creek east of the shuttle landing facility and about 1 km east of mill #12. Mill #12 did not measure a field under this cell, which died rapidly, and 5 minutes later had a maximum radar altitude less than 13,000 ft (4 km). The largest surface field measured by the field mill network occurred at mill site #22 from about 1705 to 1715 Z. At 1659 Z there was a 15,000 ft (4.6 km) echo top over the CIF, and heavy precipitation was reported west of there. By 1704 Z this cell had moved to a point about 4 km east of mill #22, and its echo top was still at 15,000 ft. By 1715 Z the echo top of this cloud had grown to 18,000 ft (5.4 km), and the cell was now about 2 km east of mill #22. At 1715 Z SPTVAR, headed south, passed about 3 km east of mill #22 as shown in Fig. 20. At that time mill #22 reported its largest field, $\nabla V = -944$ V/m. Figure 21 shows plots of E_Z and E_Y measured by SPTVAR between 1712 and 1719 Z while flying at 12,000 ft (3.7 km) altitude. The field affecting mill #22 did not extend to the path traversed by SPTVAR.
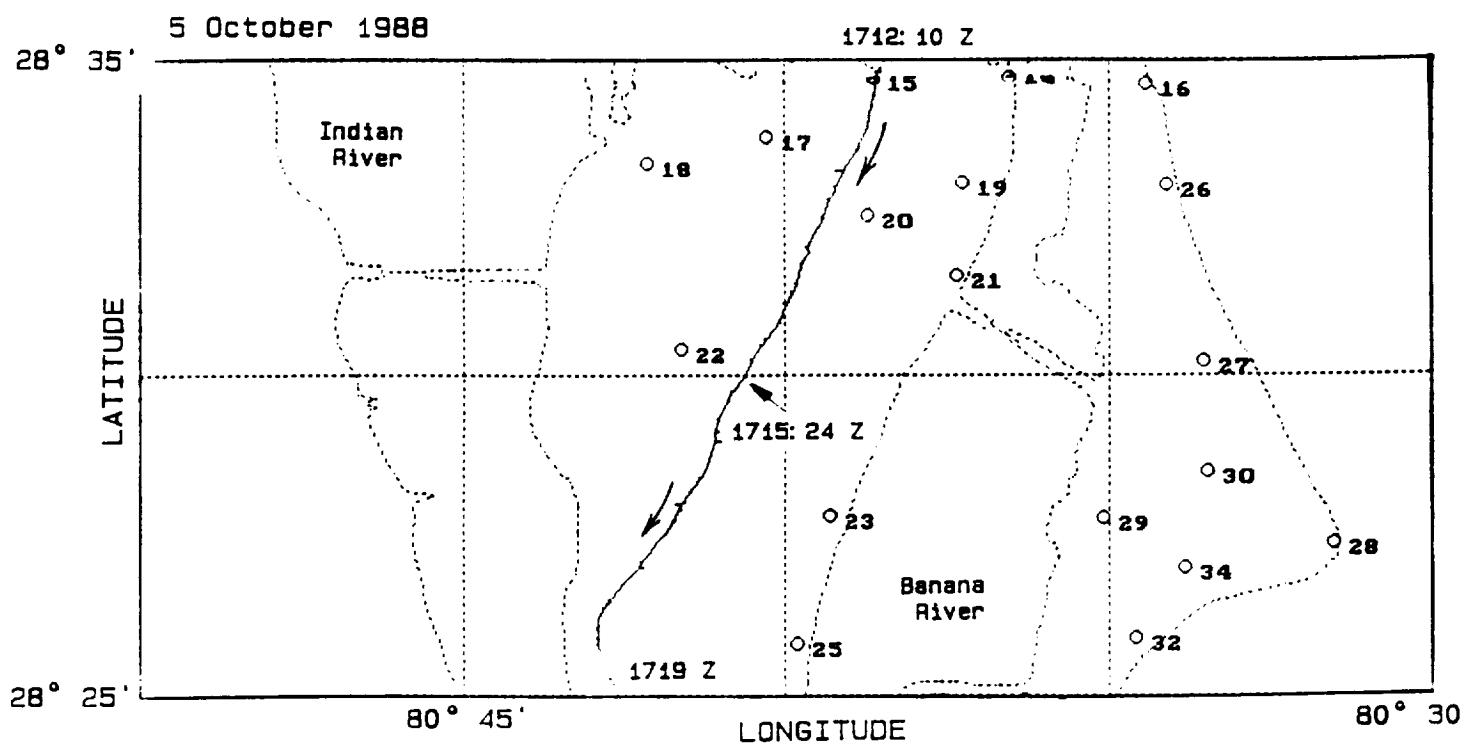
Figure 20: The 5 October 1988 SPTVAR flight track from 1712 to 1719 Z with the E_z option selected. SPTVAR passed 3 km east of mill #22 at 1715:24. The one-minute average ∇V reported by mill #22 for 1714–1715 was −944 V/m.
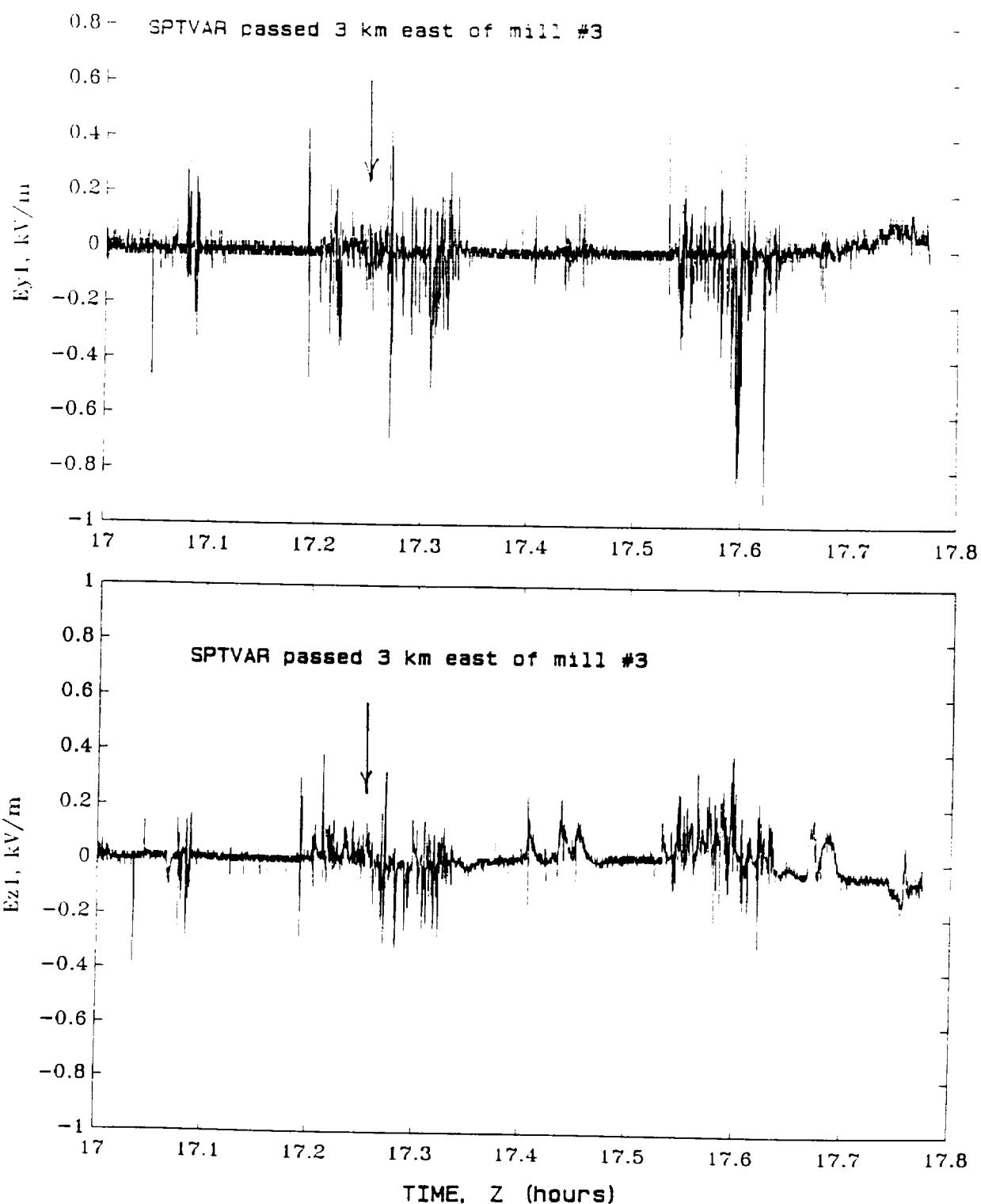
Figure 21: E_Y (A) and E_Z (B) from 1712 to 1718 on 5 October 1988. KSC field mill #22 indicated $\nabla V = -944$ V/m at 1715 Z, about the time the SPTVAR passed 3 km east of mill #22.

D.1.3 Summary: 14 October 1988 (88288)

On 14 October, a convergence band extended all along the east coast of the United States. At 00 Z the southern end of the band touched the Florida coast just north of the Cape. It rained during the early morning hours in various locations throughout Brevard County (in which KSC is located). At 12 Z convection was centered near Melbourne and moving toward the southwest. From the surface to 8,000 ft (2.4 km) the atmosphere was extremely moist. Below 6,000 ft (1.8 km) the winds were northeasterly in excess of 15 kph. The wind veered (clockwise) with height from 60 degrees at 5,000 ft (1.5 km) to 325 degrees at 10,000 ft (3 km), above which the winds became more westerly and picked up speed. The morning CCAFS sounding measured 0 °C at 12,500 ft (3.8 km), lower than the typical altitude of 15,000 ft (4.5 km). [Skew T diagrams for the 12 Z West Palm Beach and 13 Z Tampa soundings are shown in Fig. 22.]

SPTVAR entered the CCAFS/KSC area about 1230 Z. Clouds over the area were a double layer with the bottom of the first deck at about 3,000 ft (0.9 km) and the bottom of the second deck at about 4,500 ft (1.4 km). The decks were continuous except for broken sky conditions over the north part of the KSC area. SPTVAR climbed to 7,000 ft (2.1 km) and the pilot reported at 1257 Z that there were no cloud tops in excess of 8,000 ft (2.4 km), which was below the freezing level. SPTVAR made several passes through a cumulus with an 8,000 ft (2.4 km) top. The flight track for this day, made with the E_z barb option, is shown in Fig. 23. The lack of E_z barbs along the track in Fig. 23 imposes the constraint $|E_z| < 1$ kV/m. The strip chart record of E_z made during the flight provides the tighter constraint of $|E_z| < 250$ V/m for the entire flight. Indeed, fair weather fields prevailed throughout the flight both at SPTVAR and over the KSC field mill network.
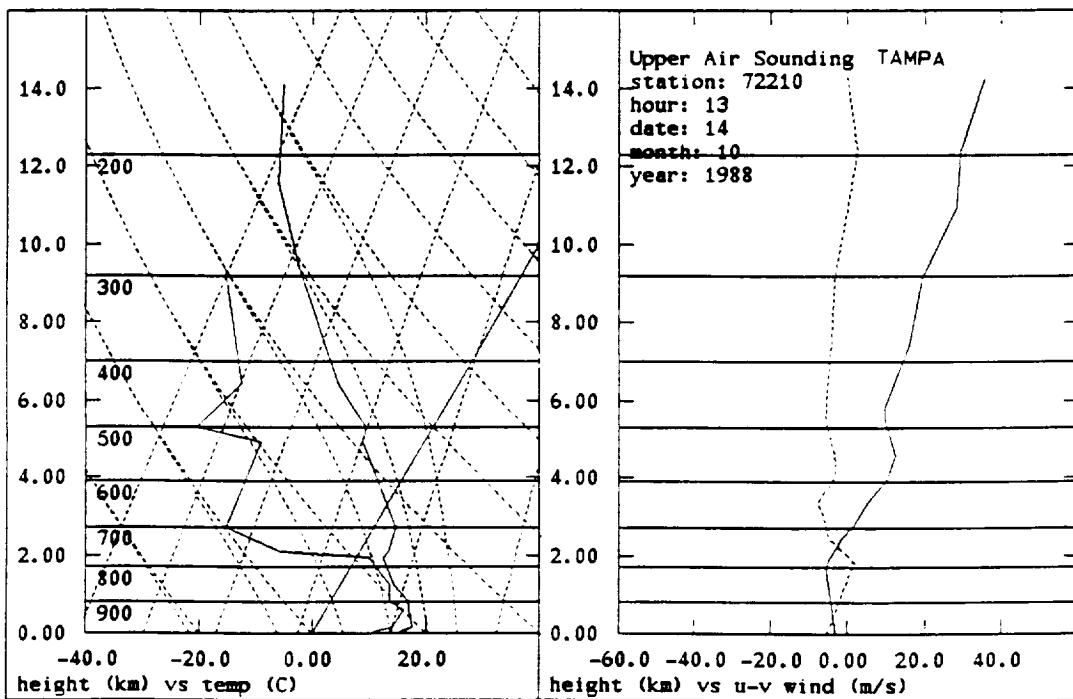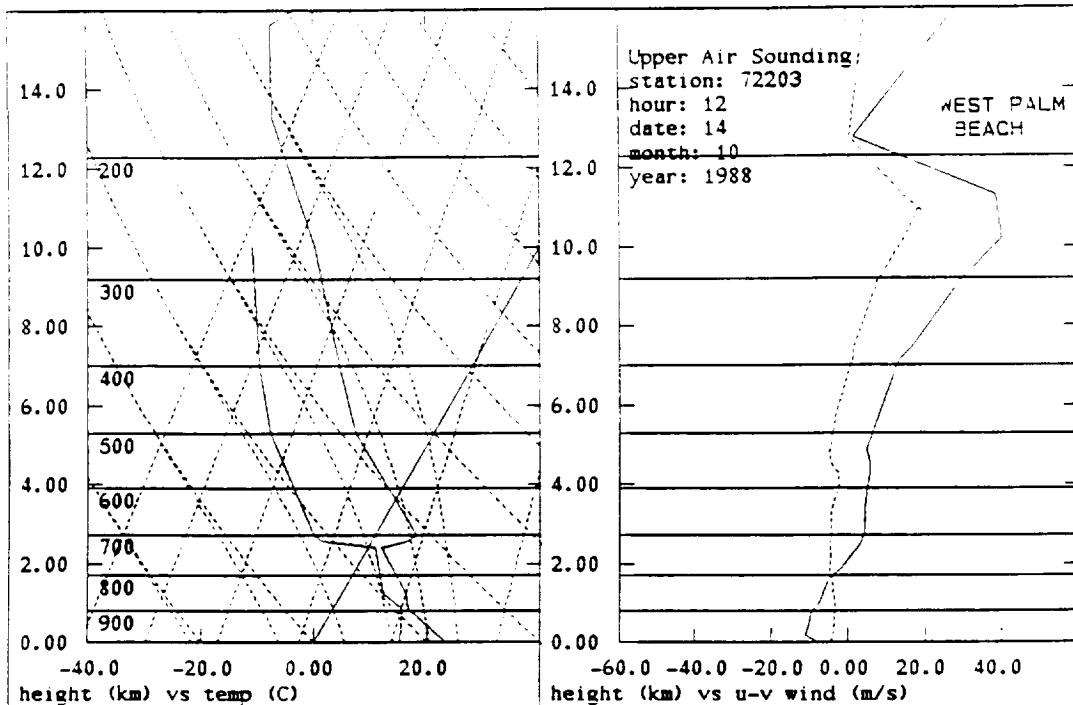
Figure 22: The Skew T diagrams for the 12 Z West Palm Beach (A) and 12 Z Tampa, Florida, (B) soundings on 14 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.
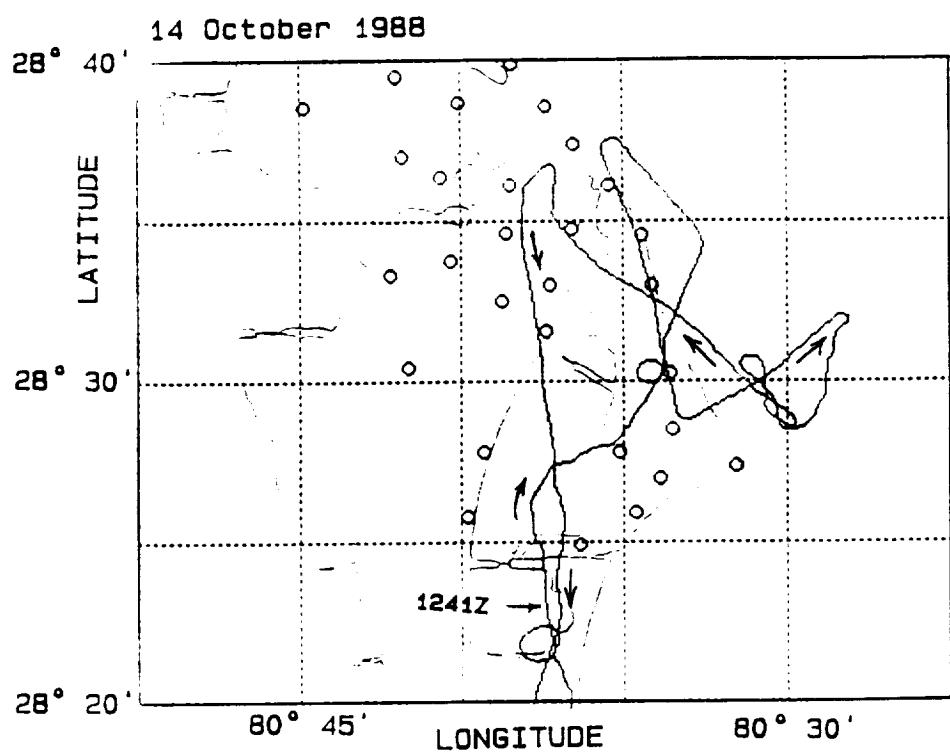
Figure 23: The flight track of SPTVAR with the E_Z barb option selected for 14 October 1988. The lack of barbs along the track indicates $|E_Z| < 1$ kV/m for the entire flight.

D.1.4 Summary: 16 October 1988 (8829)

On 16 October the satellite images showed several areas of convergence that moved from offshore of the east coast onto the south-central Florida peninsula. The atmosphere was moist to 7,000 ft (2.1 km) and extremely dry above that level. Easterly winds extended up to 12,000 ft (3.7 km). Between 9,000 ft and 15,000 ft (2.7 and 4.6 km) the winds backed (counterclockwise) with height, shifting from east-northeasterly to west-northwesterly. The second convective system of the day began influencing the CCAFS/KSC area about 10 Z. The northern edge was just north of KSC with cumulus over Mosquito Lagoon. The convection that affected CCAFS/KSC between 10 and 14 Z was a narrow east-west band associated with a larger cloud mass that remained offshore until 1430 Z. Rain showers and lightning reportedly were associated with the main part of the cloud band. [Skew T diagrams for the 12 Z West Palm Beach and 13 Z Tampa soundings are shown in Fig. 24.]

SPTVAR flew between 1146 and 1312 Z. The flight track for this flight, made with the E_Z barb option, is shown in Fig. 25. The objective was to study morning clouds. After take-off SPTVAR flew along the coast line to the line of clouds which crossed the coast just north of the KSC area. The airplane, now at 10,000 ft (3 km) altitude, penetrated first one and then another of these clouds which were over the north end of the Indian River. By 1230 Z the cloud activity was diminishing so SPTVAR descended to 8,000 ft (2.4 km) and moved a short way offshore where it penetrated clouds, one of which had high LWC. Most of the clouds over land did not go much above 10,000 ft (3 km) and there were no tops above 12,000 ft (3.7 km). Fair weather electric fields prevailed throughout the flight both at SPTVAR and over the KSC field mill network.
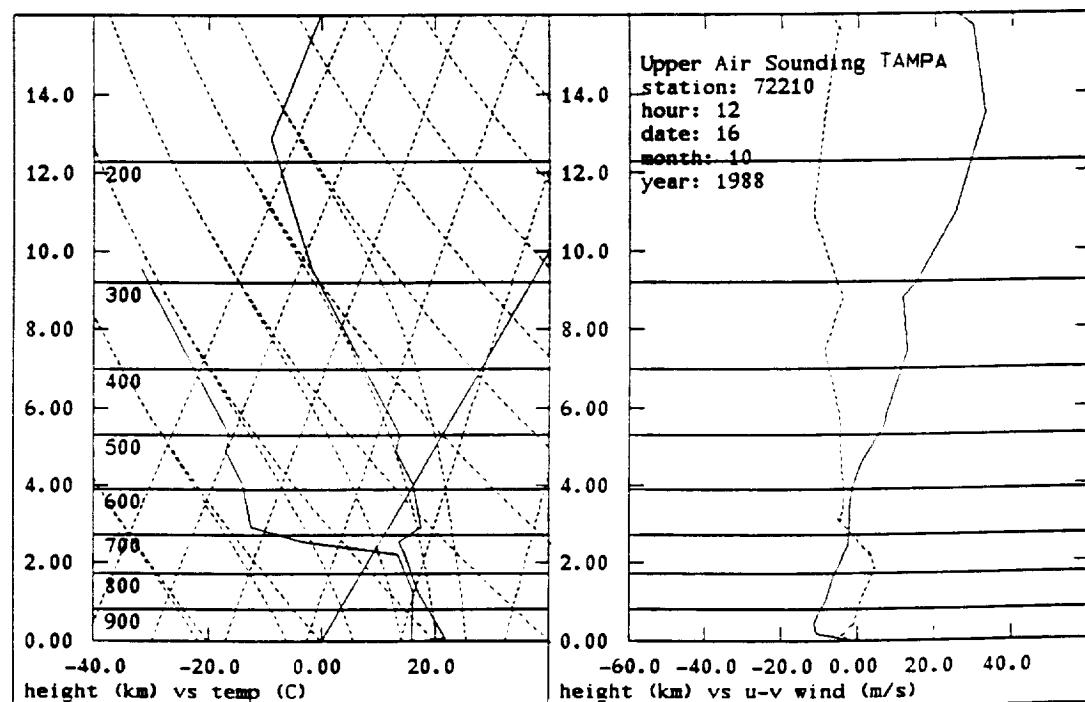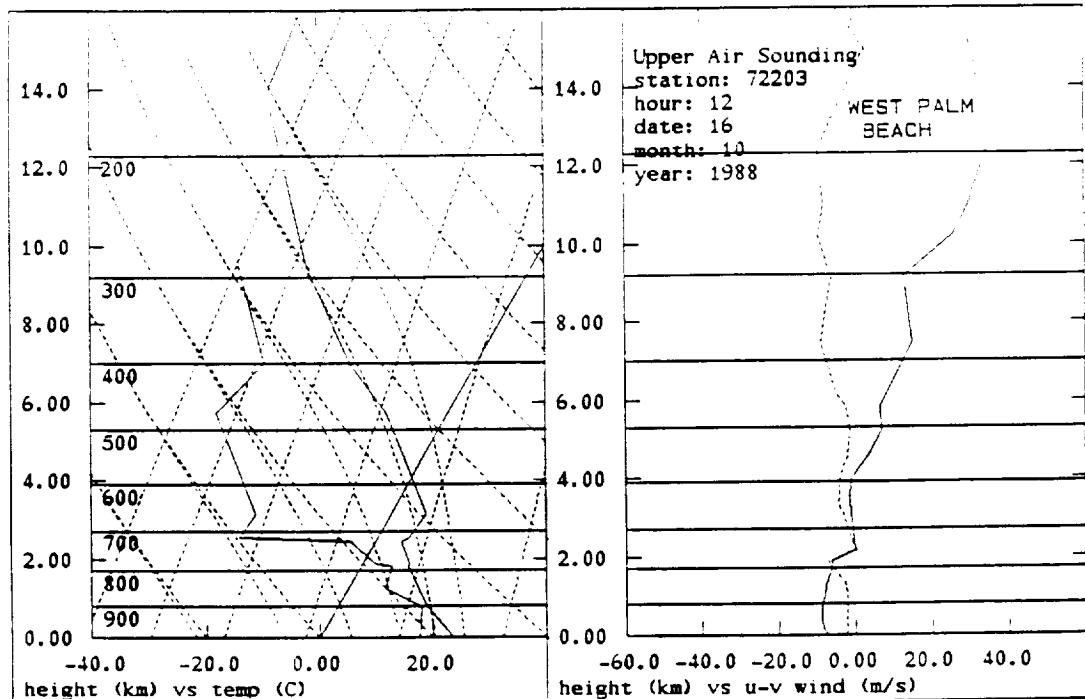
Figure 24: The skew T diagrams for the 12 Z West Palm Beach (A) and 13 Tampa, Florida, (B) soundings on 16 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

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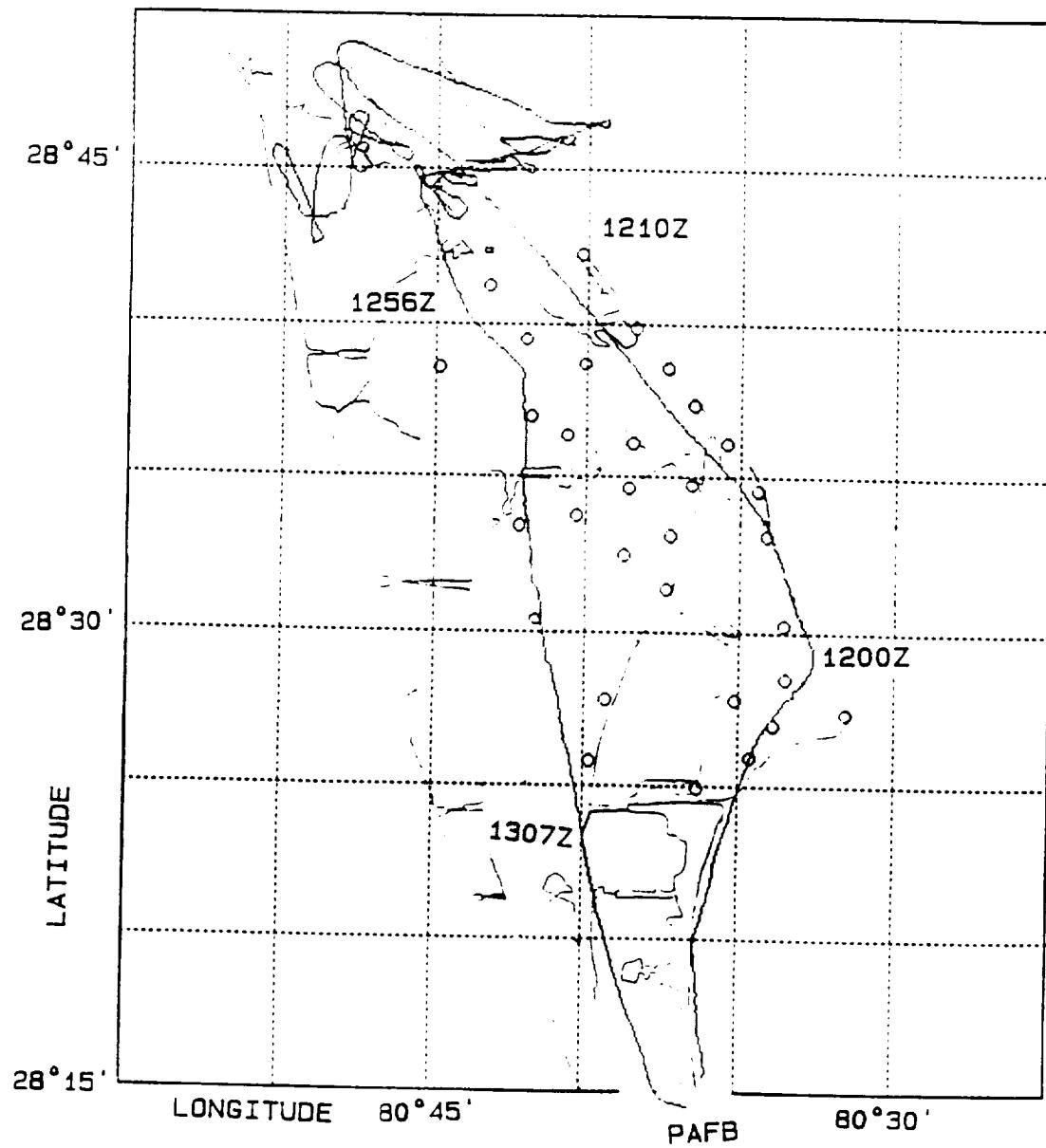
Figure 25: The ground track with the E_z option selected for the 16 October 1988 SPT-VAR flight. The lack of barbs along the track indicates $|E_z| < 1$ kV/m for the entire flight.

D.2 Early morning cumulus—no convergence.

The SPTVAR flights of 16 September and 7 and 8 October 1988, with take-off times of 5:42, 6:13 and 6:19 AM EST, were conducted with the objective of studying morning clouds. There were no convergence zones associated with the clouds studied on these three days. In the following discussions, the weather synopses are based on the daily synoptic summaries prepared by Ms. Launa Maier.

D.2.1 Summary: 16 September 1988 (88260)

On 16 September the dominant weather feature was Hurricane Gilbert which came ashore later in the day approximately 160 km south of Brownsville, Texas. A feeder band that produced bountiful cloud cover and scattered rain showers the day before moved northeastward out of Florida. A high pressure ridge dominated the eastern United States and produced easterly flow up through 25,000 ft (7.6 km). There was significant drying above 14,000 ft (4.3 km). [The 12 Z West Palm Beach and 1 Z Tampa, Florida, skew T diagrams are shown in Fig. 26.]

SPTVAR flew from 1041 to 1231 Z. The flight track for the entire flight is shown in Fig. 27. The clouds over KSC were dissipating as SPTVAR approached, but there were clouds over the ocean. SPTVAR flew about 30 km offshore to reach what appeared to be the best convective cloud available and penetrated it several times between 1130 and 1159 Z. The cloud was not electrified as evidenced by the lack of E_Z barbs in Fig. 27 which was drawn by SPT with the E_Z barb option selected (barbs would be visible anywhere SPTVAR measured $|E_Z| > 1,000$ V/m). The cloud electric field is further constrained by the stripchart plot of E_Z made during the flight, which shows no discernible $|E_Z| > 250$ V/m).
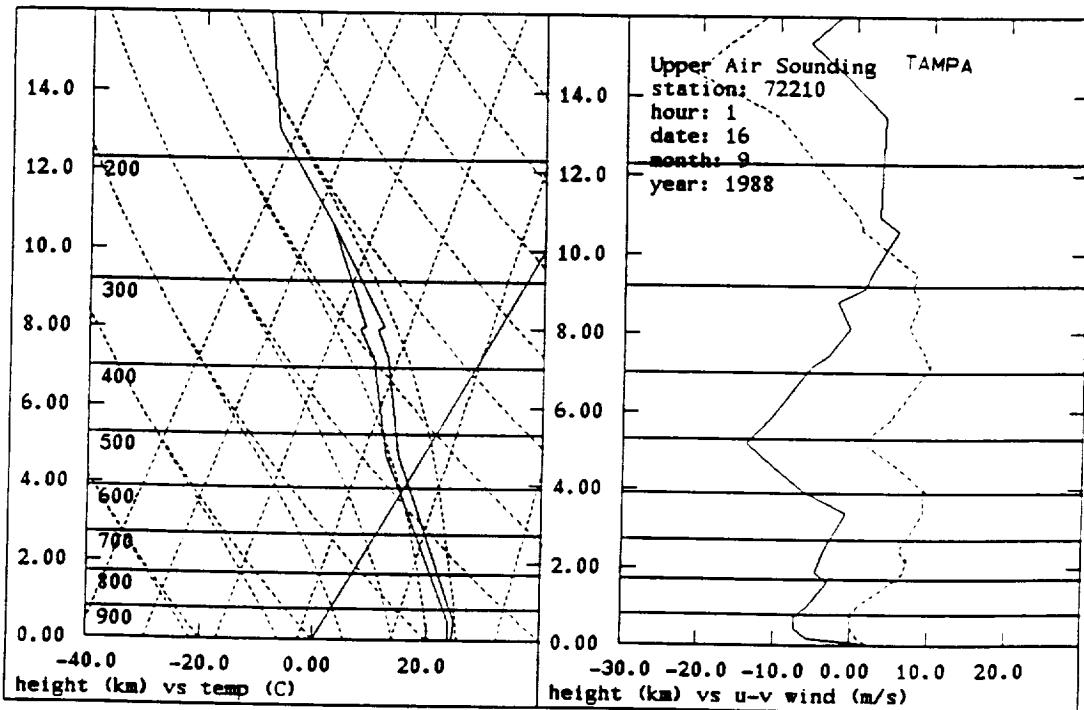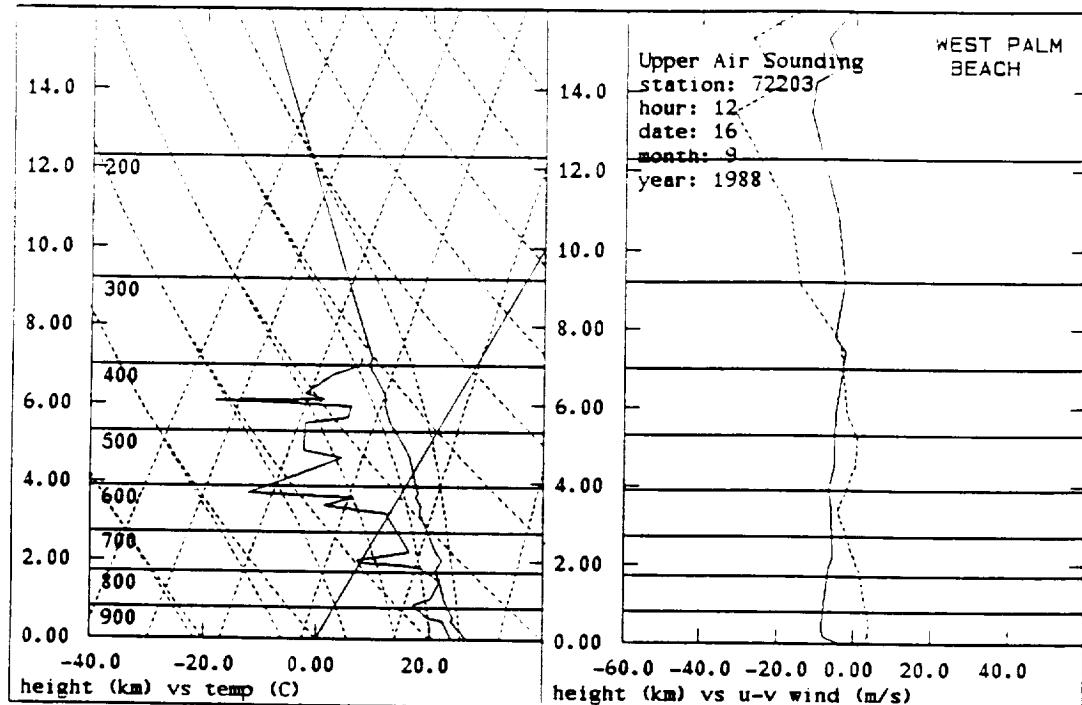
Figure 26: 12 Z West Palm Beach (A) and Tampa, Florida, (B) skew T diagrams for 16 September 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

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88260

1121z

1108z

1211z

1159z 1130z

1055z

10 km

1226z

1045z

PAFB

80°45'

80°30'

LONGITUDE

29°00'

28°45'

LATITUDE

28°30'

28°15'
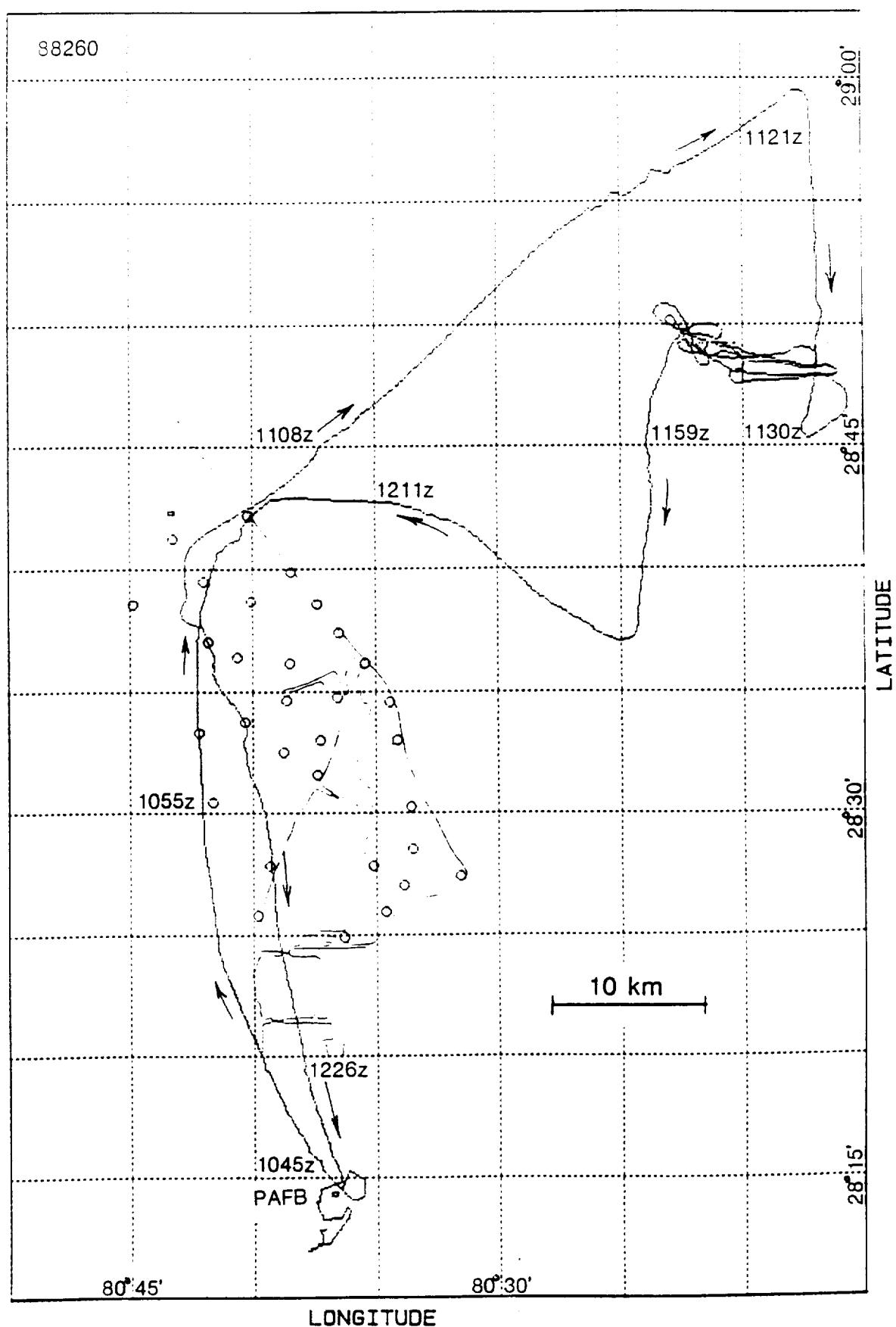
Figure 27: Flight track for 7 October 1988 with the E_Z barb option selected. The lack of barbs along the track indicates $|E_Z| < 1$ kV/m for the entire flight.

D.2.2 Summary: 7 October 1988 (88281)

On 7 October the eastern half of the United States was dominated by a long wave trough. There was a small trough between Appalatchacola, Florida, and Waycross, Georgia, at 700 mb and a stationary front located through southern Florida. The winds from the surface to 5,000 ft (1.5 km) were northerly shifting to northeasterly. The winds were out of the south at 3 knots at 6,000 ft (1.8 km) and shifted to southwesterly at 8,000 ft (2.4 km) and westerly at 10,000 ft (3 km). They were westerly from 10,000 ft to 100 mb. The surface to 5,000 ft (1.5 km) was very moist, but above 10,000 ft there were alternating moist/dry layers 4,000 to 5,000 ft (1.2 to 1.5 km) thick.

At 12 Z the cloud cover was predominantly offshore, but extended inland about 30–50 km east of Jacksonville down to the Cape. The cumulus appeared to develop on the north side of KSC and across toward Titusville and advect southward over the field mill network. The cells could be seen on the satellite pictures as they moved over the area. Vigorous convection was over the Cape at 14 Z with tops to between 12,000 and 14,000 ft (3.7 and 4.3 km). Cell activity was more robust at this time. The 12 Z skew T diagrams for West Palm Beach and Tampa, Florida, are shown in Fig. 28.

SPTVAR flew from 1113 to 1346 Z and penetrated clouds which formed and dissipated repeatedly over KSC. The track for the entire flight is shown in Fig. 29. SPTVAR flew mostly at 6,000 ft (1.8 km), then worked up to 8,000 ft (2.4 km) near the end of the flight. A few clouds went up to 10,000 ft (3 km), and some of those that were penetrated had good vertical winds and turbulence. A few of the clouds had LWC up to 4 and 5 g/m^3, the highest ever measured with the SPTVAR! By the end of the flight, clouds over KSC were pretty dead—not much above 6,000 ft (1.8 km). $|E_z|$ at SPTVAR was less than 200 V/m for the entire flight, and all KSC mills measured fair weather fields throughout the period of the flight.

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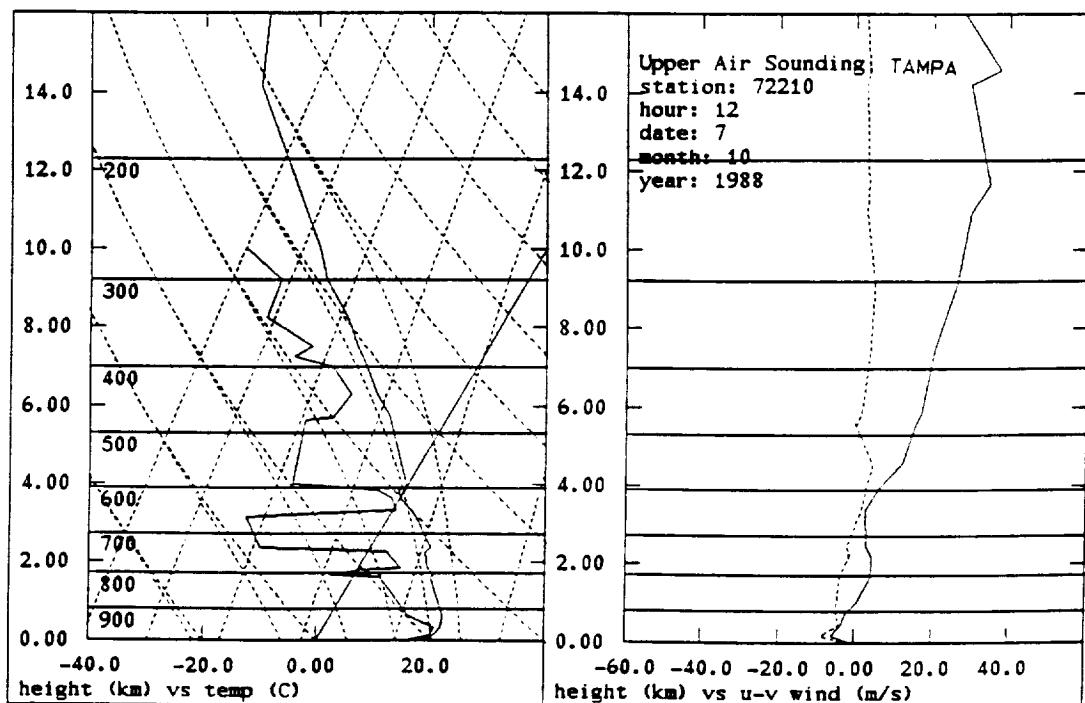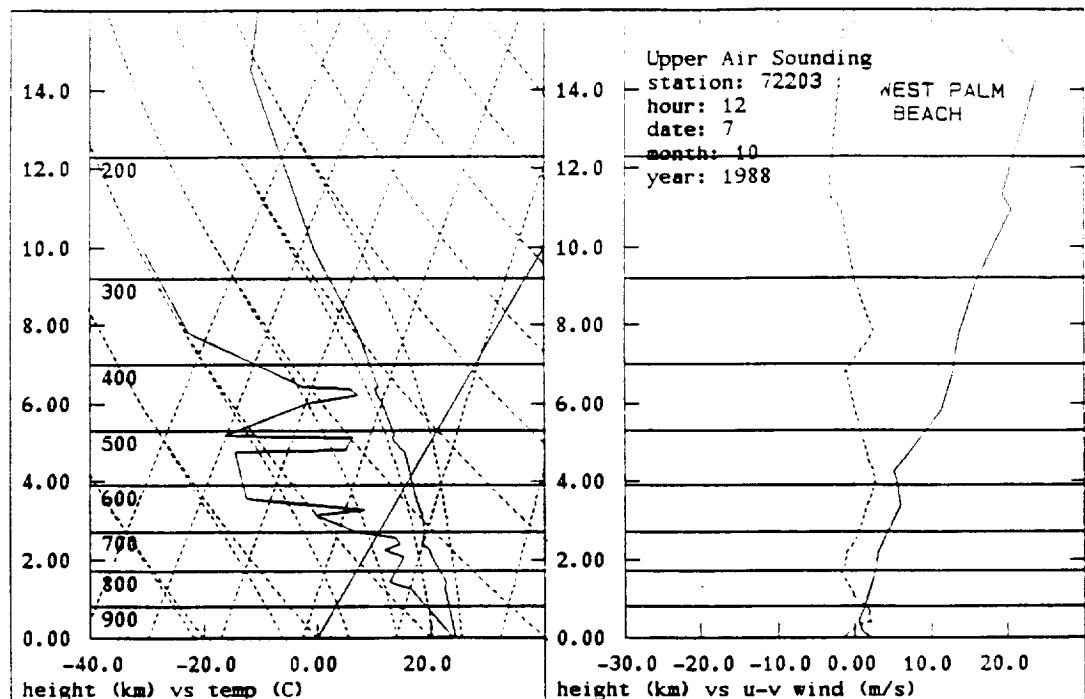
Figure 28: 12 Z skew T diagrams for West Palm Beach (A) and Tampa, Florida, (B) on 7 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

7 October 1988
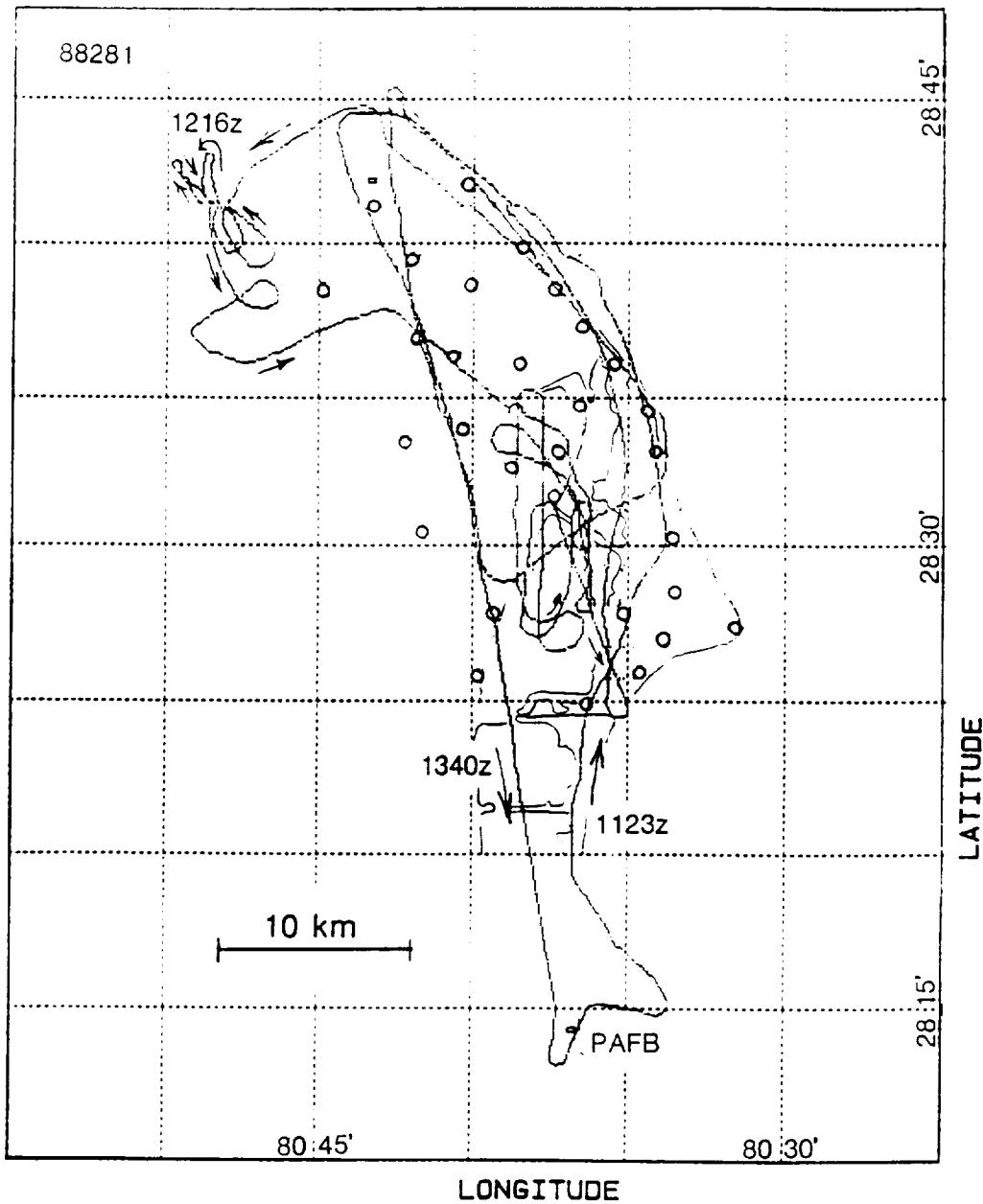
Figure 29: Flight track for 7 October 1988 with the E_Z barb option selected. The lack of barbs along the track indicates $|E_Z| < 1$ kV/m for the entire flight.

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D.2.3 Summary: 8 October 1988 (88282)

On 8 October a stationary front was located through the Florida Keys and a trough was off the coast of the Carolinas. The tail of the trough extended to the Florida east coast between Jacksonville and the Cape. The eastern two thirds of the country was under the influence of this trough. The moisture was contained in a very shallow layer between the surface and 6,000 ft (1.8 km). From 1,000 to 5,000 ft (0.3 to 1.5 km) the winds rotated from northerly to a westerly direction and maintained that direction throughout the troposphere. [Skew T diagrams were not available for this day from West Palm Beach or Tampa, Florida.]

On the GOES water vapor images a significant dry slot ran east-west through the Cape and over towards Tampa. At 09 Z there was a triangular region of clouds approximately 80 km off the coast south of Jacksonville. There were isolated low level clouds along the coast during the early morning hours as seen in the GOES IR images. The activity moved southward with time.

SPTVAR flew from 1119 to 1307 Z. Figure 30 shows the complete track plot for this flight (with E_Z barb option selected). Convection appeared to have peaked shortly after dawn and then became ragged and more disorganized with time. The clouds rarely got above 8,000 ft (2.4 km) in the local area. SPTVAR penetrated tops of some clouds in the later half of the flight, descending eventually to 7,500 ft (2.3 km) in order to do so. No turrets persisted, the cloud growth was slow and the tops moved to the southeast. There were no electric field values other than fair weather ones observed by the aircraft or the KSC field mill network.
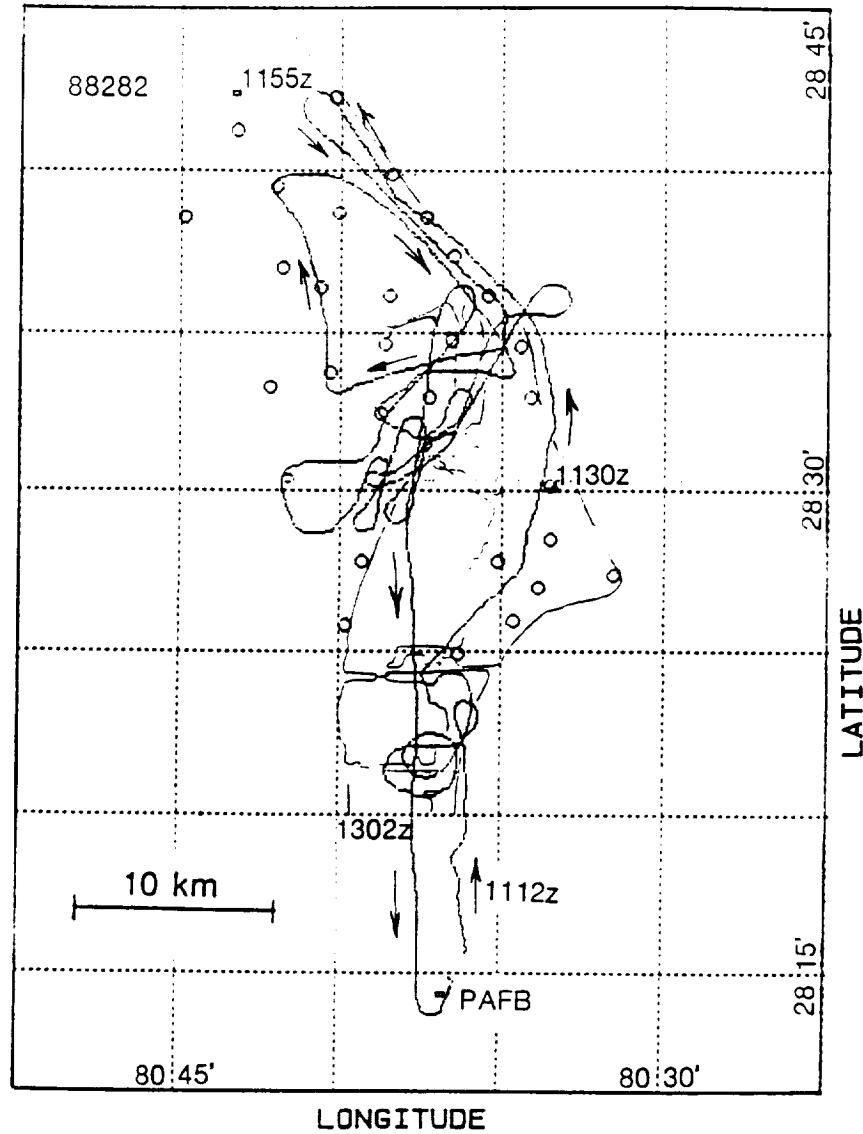
Figure 30: Flight track for 8 October 1988 with the E_z option selected. The lack of barbs along the track indicates $|E_z| < 1$ kV/m for the entire flight.

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D.3 Midday sea breeze clouds.

Four flights were conducted with SPTVAR to study midday sea breeze clouds. They were the flights of 19 and 20 September and 6 and 20 October, take-off times of 1:35 PM, 10:09 AM, 1:32 PM and 1:40 PM EST. In the following discussions, the weather synopses are extracted from the daily synoptic summaries prepared by Ms. Launa Maier.

D.3.1 Summary: 19 September 1988 (88263)

On 19 September sea breeze clouds formed over the Indian River and moved west. There were no clouds over KSC. [Skew T diagrams for the 12 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 31.]

All of NASA's restricted areas were closed for a test that took place at about 12:50 EST (1750 Z). SPTVAR went southwest of Patrick about 50 kilometers to fly through some clouds with tops generally at or below 10,000 ft (3 km), although some clouds that SPTVAR penetrated had higher tops. The SPTVAR track for this flight, lasting from 1835 to 2024 Z, is shown in Fig. 32.

Once, in a rainshaft below a turret remnant at about 1947–1948 Z (19.78–19.8 decimal hour Z), SPTVAR measured a very weak E_Z of about +250 V/m. Plots of the components of E measured by SPTVAR at that time, shown in Fig. 33, indicate a small positive free charge in the rainshaft just below the SPTVAR altitude. Since the threshold for drawing barbs was set at 1 kV/m in Fig. 32, there is no indication of this rainshaft charge in that figure. However, Fig. 32 does show a few small barbs indicating $|E_Z| > 1$ kV/m and negative at several times between 1930 and 2000 Z, during which time SPTVAR was flying at about 10,000 ft (3 km) altitude where the temperature was about 9 °C. Figure 34 shows a detailed plot of field components, airplane charge-field and LWC as a function of time for that interval. In the figure, time is plotted as decimal hours. The LWC plot is presented at the bottom of *each* column of figures since the LWC was the cause of all the airplane charge and, except for that at 1948 Z (19.8 Z), the electric field components shown in the plots. Note that E_Z was constant and effectively zero right up to the times LWC was encountered, and once again flat as soon as SPTVAR exited the regions of LWC. These field component excursions during cloud penetrations are the result of heavy charging of SPTVAR by the high liquid water concentrations encountered. This strong charging is balanced by the emission of charge as corona from various "points" on the airplane's exterior. The emitted charge forms plumes, the electric field of which may be strong enough, as in this case, to cause significant anomalous fields at the SPTVAR mills. Figure 34 indicates that the E_Z measured in the rainshaft was the largest ambient atmospheric field measured by SPTVAR during this two-hour interval.
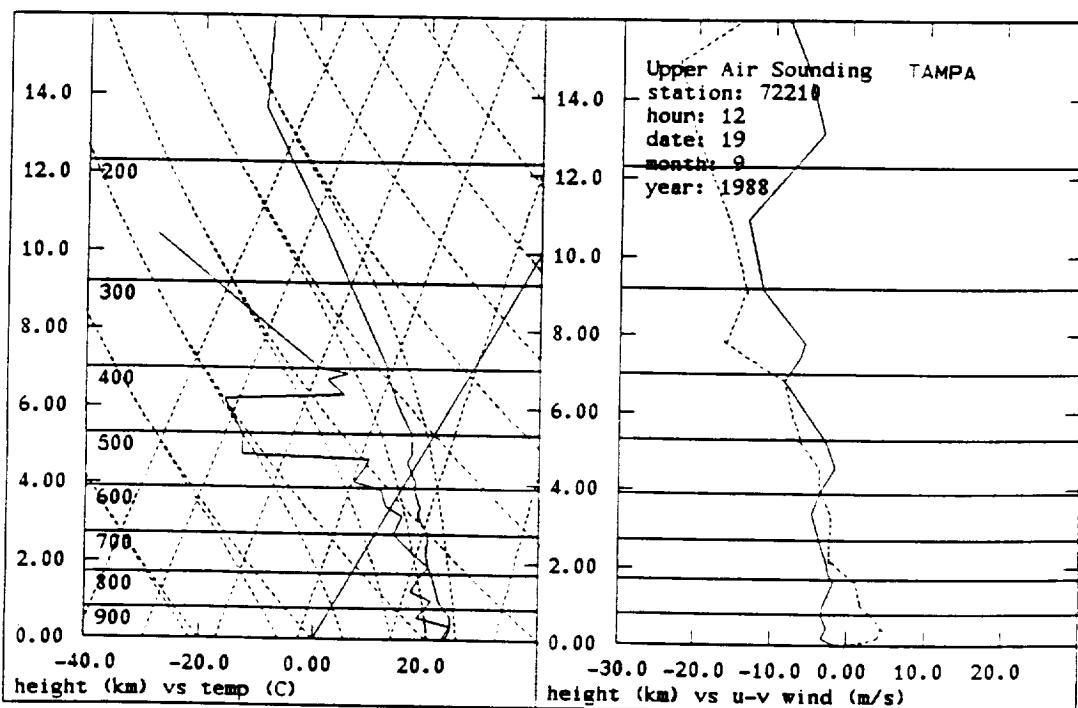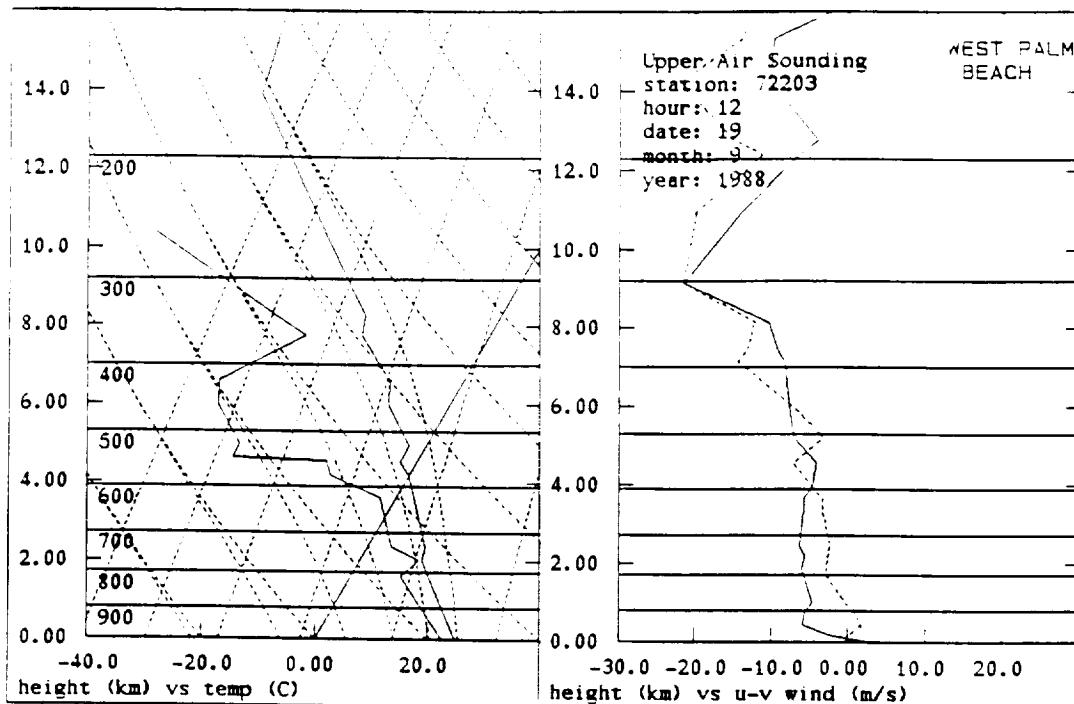
Figure 31: 12 Z West Palm Beach (A) and Tampa, Florida, (B) skew T diagrams for 19 September 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.
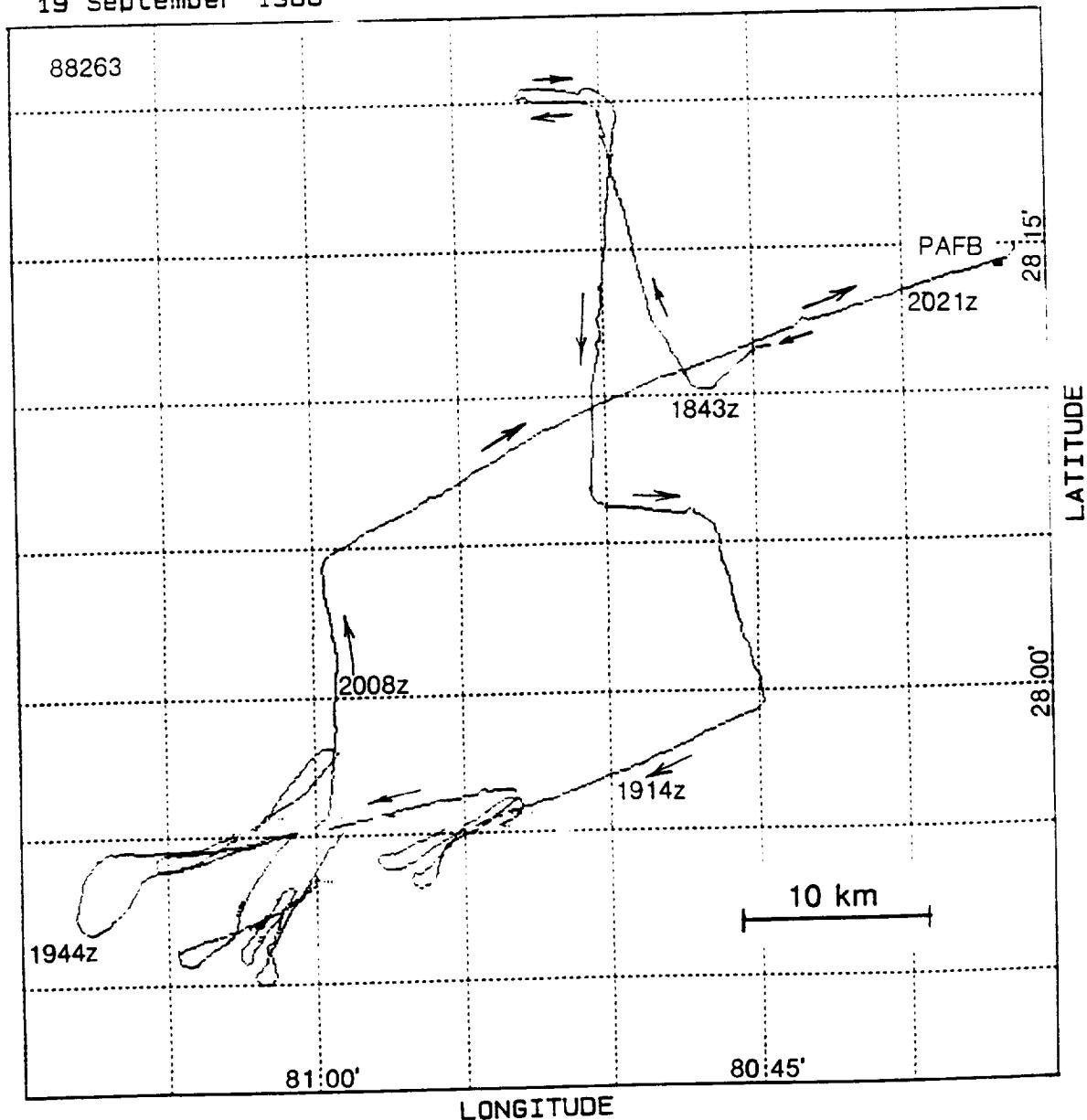
Figure 32: Flight track for 19 September 1988 with the E_z barb option selected.
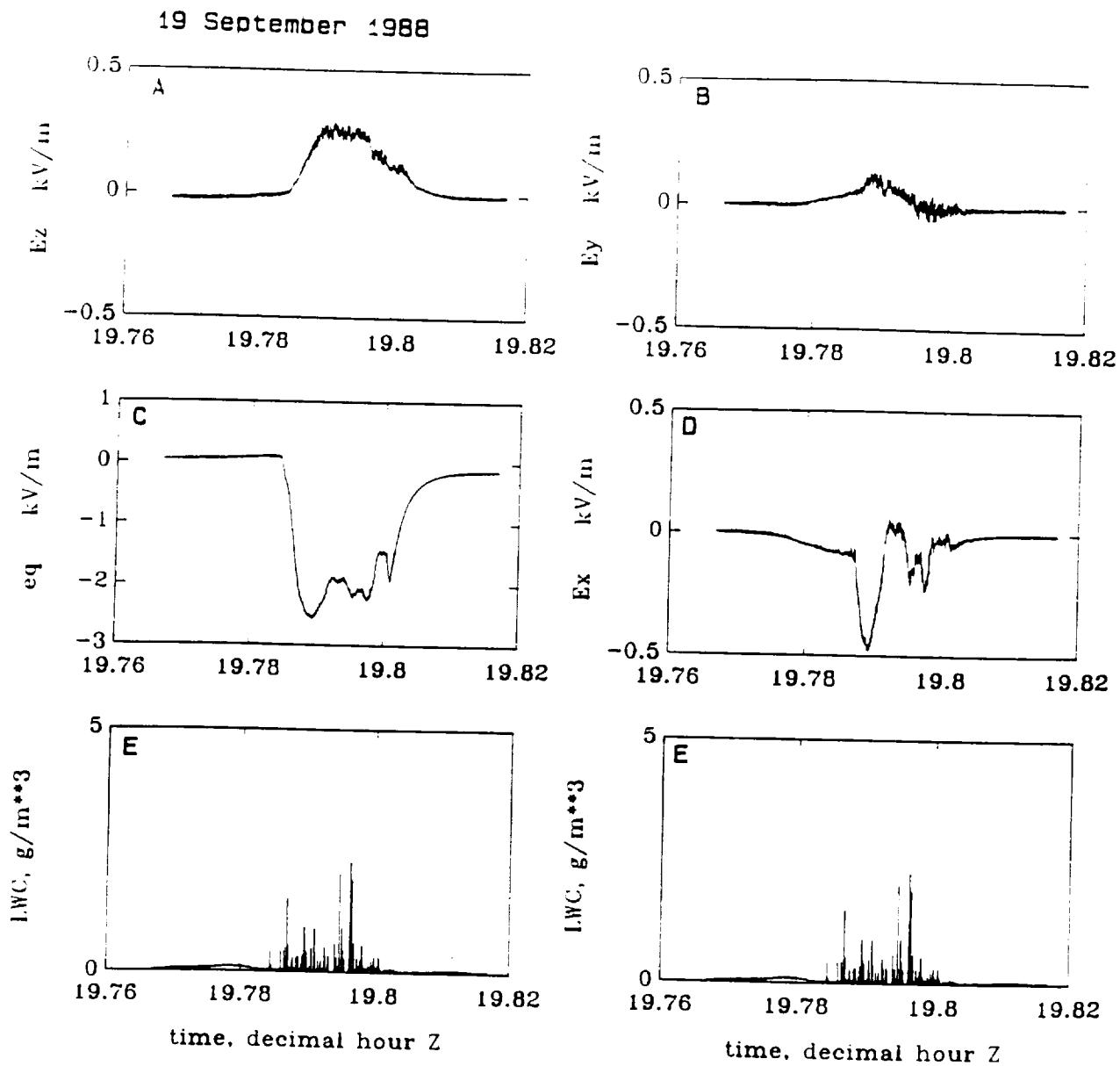
Figure 33: The E field components measured in a small rainshaft on 19 September 1988 (from the high sensitivity signals). The LWC and the airplane charge-field are included and indicate that the charging of SPTVAR was related to the LWC.
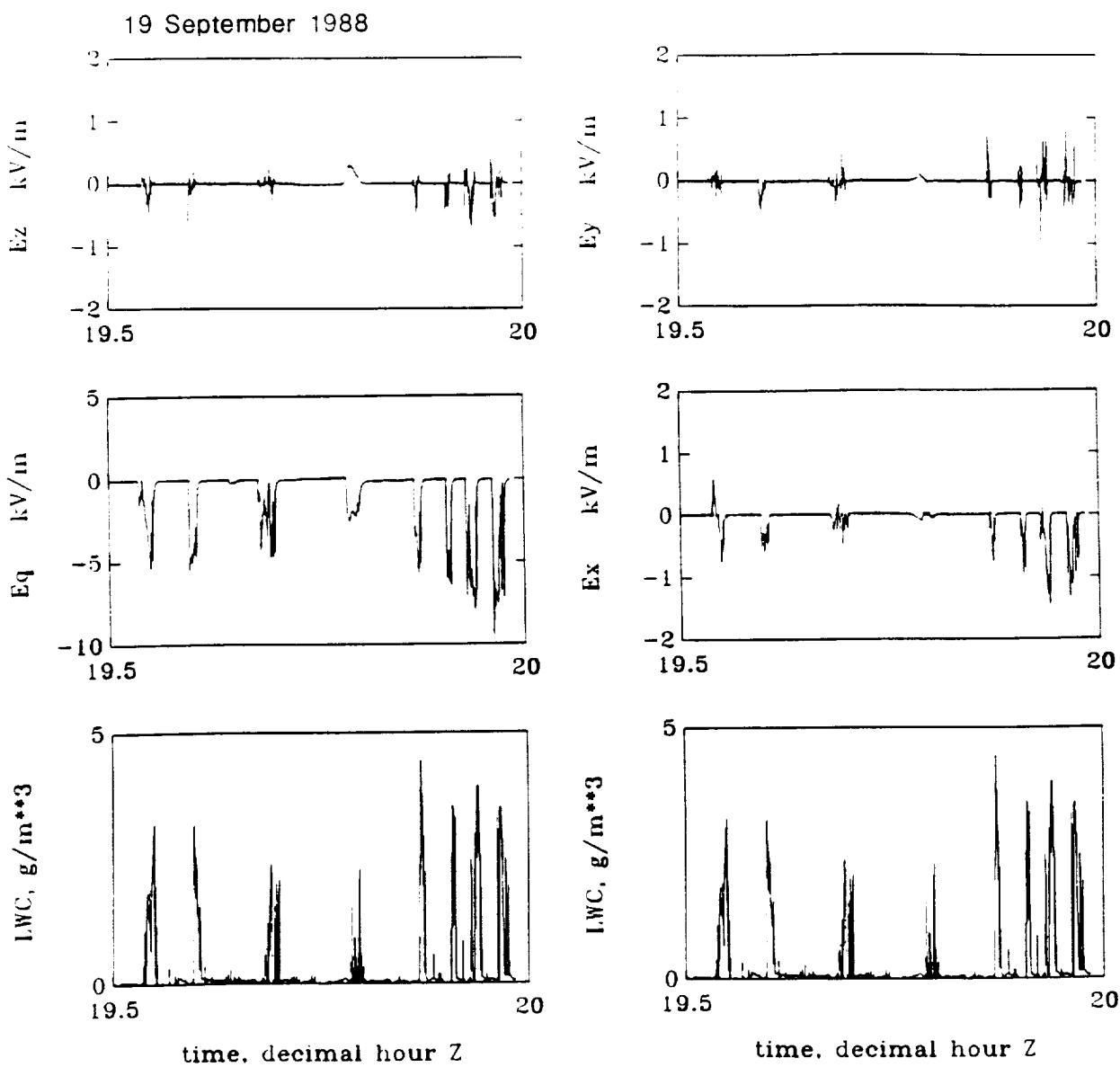
Figure 34: LWC, airplane charge-field and E field components for the thirty-minute interval 1930 to 2000 Z on 19 September 1988. A true ambient field was measured in the rainshaft at 19.8 Z (1947–1948 Z), shown in more detail in the previous figure. All the other E field component excursions shown here were due to charge plumes resulting from charging of the airplane by the LWC.

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Figure 34 illustrates how charge plumes, due to charging of the SPTVAR by an interaction with the LWC, limit the measurement of field components when the field is small. E_Z of the magnitude measured in the rainshaft at 1948 Z would be difficult to identify if it had occurred during one of the cloud penetrations where the LWC was high. Both E_Y and E_X in the rainshaft were too small to have been resolved in the presence of significant corona charge plumes. During the later part of the interval shown in Fig. 34 where the LWC was above 3 g/m^3, there are brief false excursions of E_Z to about −350 V/m and E_X to about −1 kV/m. Thus a true E_Z of 250 V/m and E_X of 1 kV/m might be masked by the field from charge plumes when the LWC is high. Figure 34 also shows the electric field at the face of the top and bottom field mills $(E_{q z 1})$ due to the net charge carried on the airframe. The LWC was less during the rainshaft penetration than during the cloud penetrations so that the charging was milder and apparently did not result in corona plumes which are expected to release charge from the airframe in bursts. Note the smooth character of the curves for the electric field components and $E_{q z 1}$ at d in Fig. 34, the time of the rainshaft penetration, in comparison with the very noisy nature of these curves during the cloud penetrations (a–c, and e–h. Thus, although the SPTVAR did acquire charge while penetrating the rainshaft, it was insufficient to cause corona emission and the small field components due to free charge in the rainshaft were easily resolved. This example illustrates some of the difficulties involved in measuring electric field with an airplane when the airplane is charged, and especially when it is interacting with cloud particles.

Examination of the original strip chart recording of E_Z for the rest of this flight revealed that there was no disturbed ambient $\vec{E}$ due to cloud charge, although the LWC was considerable and good updrafts were encountered. It was difficult to get clearance to fly southwest of Patrick because of traffic in the airways, but the pilot got a Miami controller who was very helpful.

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D.3.2 Summary: 20 September 1988 (88264)

On 20 September there was a sea breeze front which was double over CCAFS. Satellite photos showed cumulus developing over the Cape, Merritt Island and the mainland. They drifted west quite slowly. Light rain was visible over Merritt Island. The wind was from the southwest from the surface to 3,000 ft (0.9 km) and from the northeast and east-northeast above 4,000 ft (1.2 km). The atmosphere was moist up to 14,000 ft (4.3 km). [The skew T diagrams for the 12 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 35.]

SPTVAR flew from 1508 to 1803 Z. Cumulus were expected to develop to the +5 °C level or higher, so SPTVAR climbed to 12,000 ft (3.7 km) and went through the tops of clouds. The pilot estimated that some tops went to 14,000 ft (4.3 km). There was high LWC. SPTVAR made passes at 10,000 ft (3 km) through a dying cloud near the end of the flight, and below the same cloud at 7,000 and 8,000 ft (2.1 and 2.4 km). The Loran C data for this flight were invalid due to shorting of the Loran antenna by rain water from the previous flight (a problem which was quickly discovered and cured). Linear plots showing the time variation of the measured LWC, charge field (E_{Qz}) and E_z for 1530 to 1730 Z are shown in Fig. 36. There were several occasions when the SPTVAR charged positively due to the LWC, a phenomenon not experienced in New Mexico clouds which have higher bases and lower LWC. The significant E_z excursions during the cloud penetrations are all correlated with high LWC. The undeflected traces of the field components on either side of the LWC and the noisy character of the traces when LWC was high indicate that the field component excursions are false and that the true ambient $|E_z|$ was < 200 V/m for the entire flight.

On the contour plots made from one-minute averages of the KSC field mill measurements, mill #33 measured a weak $\nabla V = -518$ V/m under a cloud at 1530 Z. It had measured a fair weather ∇V of +123 V/m at 1525 Z, and recovered to +178 V/m by 1545, having measured −7 and +5 V/m at 1535 and 1540 respectively. Thus the ∇V measured by mill #33 was returning to a fair weather value by the time the airplane penetrated a cloud in its vicinity at 1540 Z, having been directed there to look for an associated field in the clouds. SPTVAR did not find any evidence for disturbed atmospheric field during this and a subsequent penetration of the cloud.

Mill #16 began showing a negative ∇V at 1535 Z but was later determined to be malfunctioning. Indeed, at 1531:20 Z the strip chart recording made at the RCC shows an odd signal for mill #16, indicating that a malfunction had occurred. Thus one should not always believe the contour plots without first checking the strip chart recording of the analog mill signals.

14.0
12.0 200
10.0
8.00 300
      400
6.00
      500
4.00 600
      700
2.00 800
      900
0.00
-40.0   -20.0   0.00   20.0
height (km) vs temp (C)

14.0
12.0
10.0
8.00
6.00
4.00
2.00
0.00
-30.0 -20.0 -10.0 0.00 10.0 20.0
height (km) vs u-v wind (m/s)

Upper Air Sounding   WEST PALM
station: 72203   BEACH
hour: 12
date: /20
month: 9
year: 1988

14.0
12.0 200
10.0
8.00 300
      400
6.00
      500
4.00 600
      700
2.00 800
      900
0.00
-40.0   -20.0   0.00   20.0
height (km) vs temp (C)

14.0
12.0
10.0
8.00
6.00
4.00
2.00
0.00
-30.0 -20.0 -10.0 0.00 10.0 20.0
height (km) vs u-v wind (m/s)

Upper Air Sounding   TAMPA
station: 72210
hour: 12
date: 20
month: 9
year: 1988

Figure 35: 12 Z West Palm Beach (A) and Tampa, Florida, (B) skew T diagrams for 20 September 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

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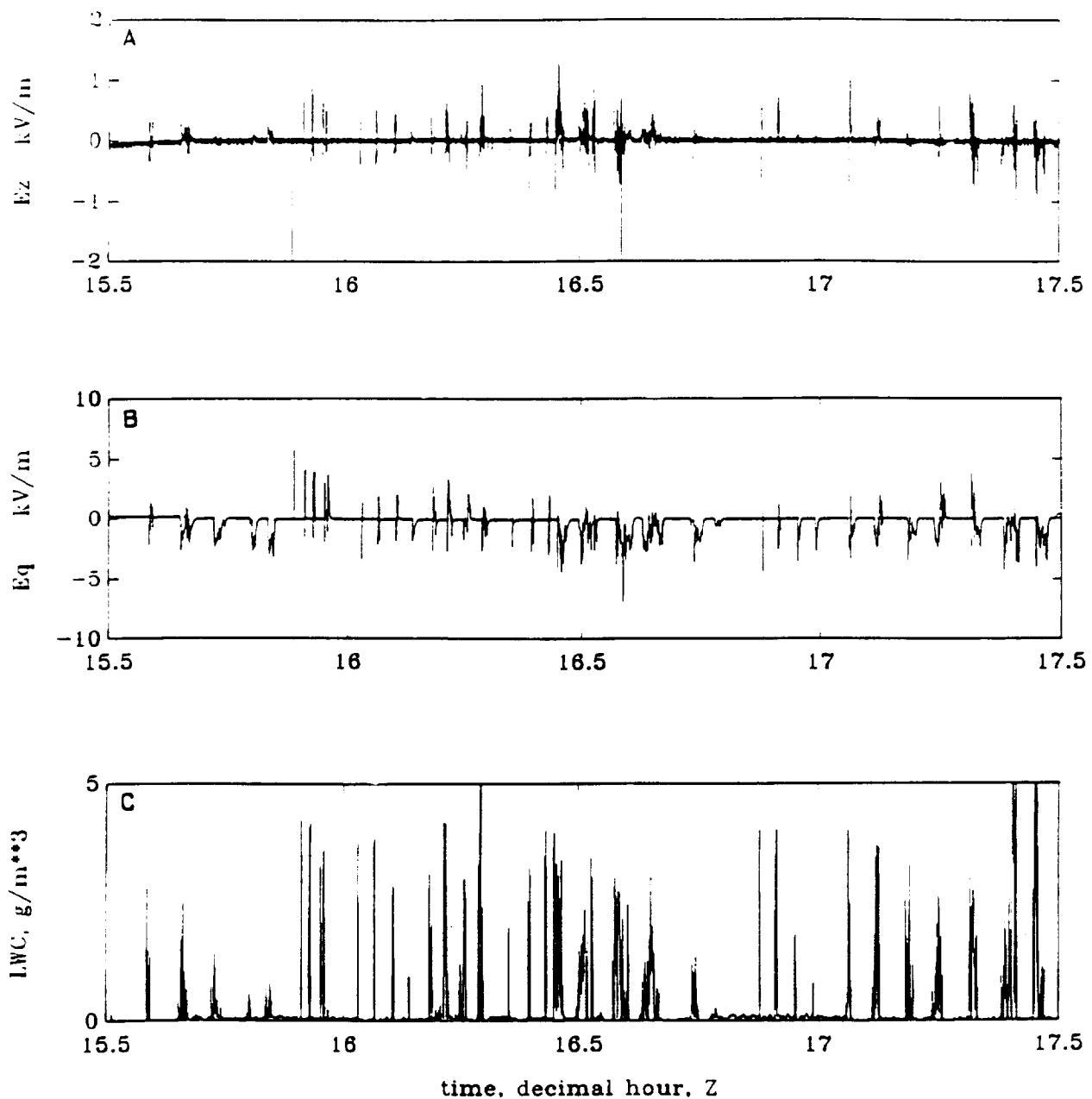
Figure 36: The LWC, airplane charge-field and E_Z for the two-hour interval 1530 to 1730 Z on 20 September 1988.

D.3.3 Summary: 6 October 1988 (88280)

On 6 October the dominant feature on the upper air charts was a long wave trough over the eastern United States. The morning sounding found the atmosphere moist through 12,000 ft (3.7 km) and very dry (relative humidity less than 20%) above this level. The surface winds were east-northeasterly and shifted more easterly up to 7,000 ft (2.1 km). The wind was southwesterly at 8,000 ft (2.4 km) and westerly above 12,000 ft (3.7 km). About 05 Z a band of clouds formed offshore of Vero Beach and Palm Beach, extending several hundred kilometers to the east. The cloud band expanded northward and was as far north as the Vehicle Assembly Building at 15 Z. The cloud band remained primarily offshore with cumulus streaks forming over the KSC/CCAFS area. The lifetimes were short and the clouds did not extend much above 10,000 ft (3 km).

The decision to fly was made when there were dark clouds over KSC and a rain shower over the Indian River west of the CIF. By the time the airplane was airborne the clouds at KSC had thinned out. SPTVAR made a short flight over the KSC area from 1822 to 1913 Z. Upon comming out the top of the clouds at about 7,500 ft (2.3 km) over Merritt Island, south of the CIF, the pilot reported no clouds higher than that altitude. A few instrumentation tests were done before the SPTVAR returned to Patrick AFB. Only fair weather electric fields were measured, both at the ground and in the air.

D.3.4 Summary: 20 October 1988 (88294)

On 20 October a long wave trough dominated the weather chart for most of the United States and there was a surface front in central Florida. The majority of the convection detected by both satellite and radar imagery was located between Jacksonville, Florida, and Daytona Beach. The winds were westerly at the surface, northwesterly between 2,000 and 10,000 ft (0.6 and 3 km) and westerly above 10,000 ft. The relative humidity was in excess of 75% from the surface to 4,000 ft (1.2 km), between 25 and 60% from 5,000 to 18,000 ft (1.5 to 5.5 km), and less than 20% above 19,000 ft (5.8 km). At approximately 14 Z convection began over CCAFS/KSC due to the onset of the sea breeze. The maximum altitude of the local convection was less than 10,000 ft. By 1730 Z all the convection was inland except on the extreme western edge of Merritt Island. This convection died about 18 Z.

By the time SPTVAR became airborne at 1840 Z the target cloud, identified earlier as a study prospect, was vanishing. However, at this same time (1840 Z) the contour plot display of the KSC field mill data, reproduced in Fig. 37, showed that mill #32 was

indicating a ∇V of -3623 V/m while all the other mills were measuring fair-weather fields. The previous contour plot display, at 1835 Z, had shown a ∇V value of $+150$ V/m for mill #32, in agreement with all the other mills. At 2-1/2 and 5-1/2 minutes after takeoff the pilot reported that the target cloud was not in sight. At this time, 1845 Z, the mill #32 measurement was back to $+154$ V/m, once again in agreement with all the other mills, so it was decided to send SPTVAR after the best convective cloud in sight. SPTVAR started to chase this cloud, which was well out to sea. On the way, the pilot reported scattered clouds over KSC with tops generally at 3,000 ft (0.9 km), and that there were no clouds over CCAFS. The flight path of SPTVAR is shown in Fig. 38.

When it became clear that the cloud being sought was farther out to sea than originally estimated and not a useful target for study, the SPTVAR changed course and flew back west to the north end of the Indian River. As there were still no clouds, SPTVAR flew about for a while, then dropped to 1,000 ft (0.3 km) north of mill #1, and followed the coast down to about mill site #9 before returning to Patrick AFB. The radio navigation system did not operate all the way down the coast while flying at 1,000 ft and the Loran C ceased to function at and below 600 ft altitude. SPTVAR did not encounter any clouds on this flight, and measured no disturbed atmospheric electric fields.

The anomalous measurement of -3623 V/m by mill #32 at 1840 Z is not an uncommon occurrence. Indeed, there were other examples of similar isolated anomalous mill measurements earlier on this day. Field mill #25 measured -3618 V/m at 1640 Z, mill #4 -495 at 1700 Z, mill #23 -2767 at 1705 Z, mill #21 $+2062$ at 1730 Z and mill #27 $+1205$ at 1805 Z. The very brief and isolated nature of these measurements suggests that they must have been due to a local phenomenon, such as an instrumentation effector electrically charged rain near the ground (note the electric field associated with rain on 19 September), although no rain was reported by the CCAFS weather observer on this day. We do not have the original field mill strip charts for this day, and so cannot inspect the continuous analog record of the mill signals. However, it is worth noting that in each of these cases the contour plot display was cause for concern, especially for the 1705 and 1840 Z incidents. On the 1705 Z contour plot, reproduced in Fig. 39, there is a rather large closed $\nabla V = 0$ contour and two smaller circular contours enclosing mill site #23. Upon closer scrutiny it becomes clear that all of these contours are inside the boundary established by the nearest field mills (#25, #22, #21, #29 and #33), all of which were reporting fair-weather fields. Since the fair-weather fields reported by the nearby mills were all only about 3% of the mill #23 measurement, the zero contour was drawn very close to them. The contour plotting routine draws in all intervening contour levels. It has thus given the measurement from the one anomalous mill much more weight, visually, than is justified. In this example the area of the contour plot influenced by this single anomalous mill measurement is a disproportionately large fraction of the area covered by the ground-based field mill network at KSC. The visual effect is especially misleading since the contour plots do not show the locations of the individual field mills (the mill locations shown in Figs. 37 and 39 have

20 OCT 1988
1840802
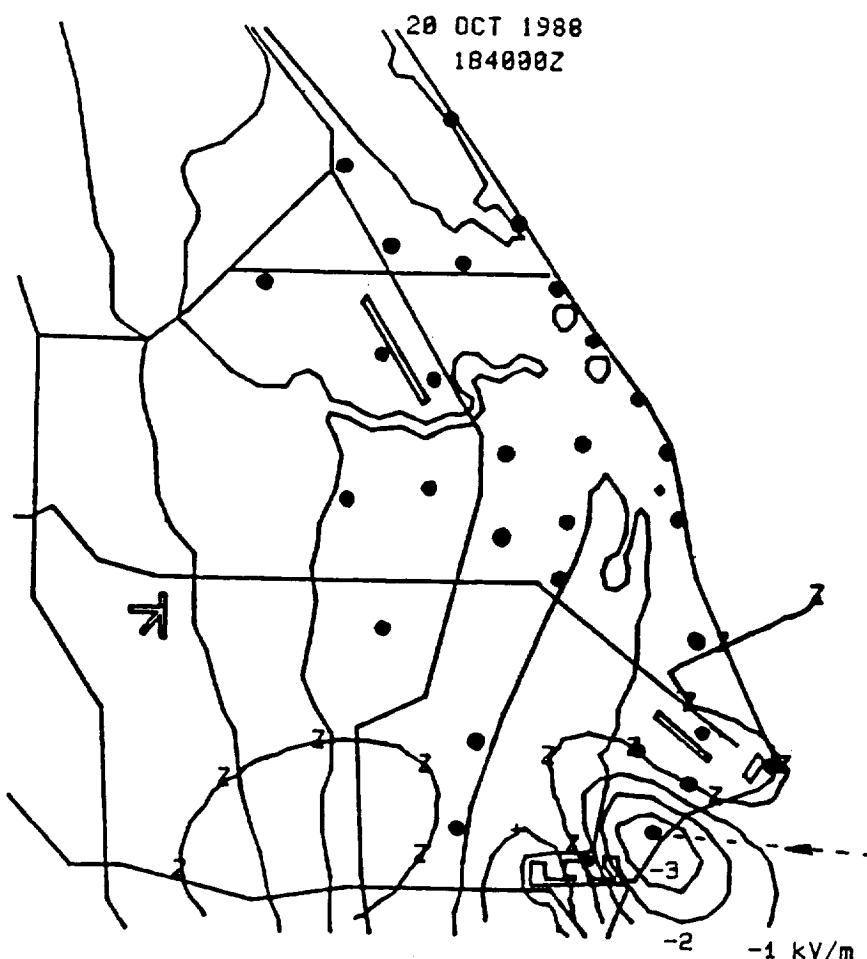
STATIC CONTOUR
05 MINUTE INTERVAL
1000 VOLTS/MTR
MILL   VOLT/MTR
01   000296
02   000324
03   INACTIVE
04   000357
05   000232
06   000212
07   000240
08   000432
09   000173
10   000221
11   INVALID
12   000209
13   000241
14   000181
15   000182
16   000212
17   000210
18   000210
19   000121
20   000204
21   000120
22   000185
23   000183
24   INACTIVE
25   000174
26   000230
27   000209
28   000195
29   000234
30   000178
31   INACTIVE
32   -03623
33   000120
34   000194
35   INACTIVE

-3

-2   -1 kV/m

Figure 37: Contour plot of one-minute averages of KSC field mill readings for 1840 Z on 20 October 1988. The contour pattern around mill #23 is prominent.
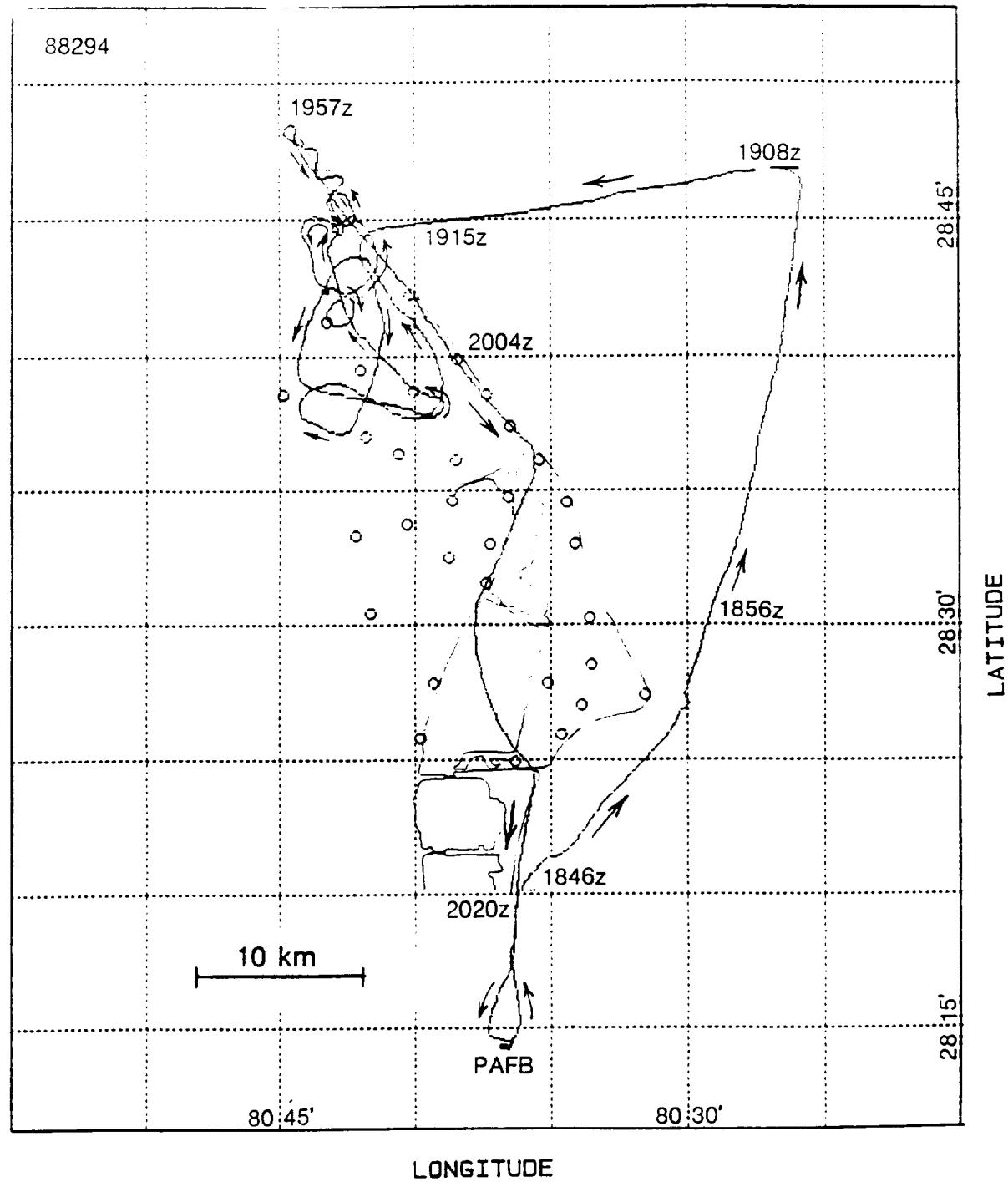
Figure 38: The flight path of SPTVAR on 20 October 1988. The lack of barbs along the track indicates $|E_z| < 1$ kV/m for the entire flight.

20 OCT 1988
1705002

STATIC CONTOUR
05 MINUTE INTERVAL
1000 VOLTS/MTR

| MILL	VOLT/MTR
01	000363
02	000225
03	INACTIVE
04	000454
05	000219
06	000207
07	000236
08	000397
09	000254
10	000266
11	INVALID
12	000164
13	000385
14	000206
15	000210
16	000408
17	000213
18	000210
19	000179
20	000237
21	000178
22	000119
23	-0276?
24	INACTIVE
25	000201
26	000319
27	000195
28	000229
29	000209
30	000210
31	INACTIVE
32	000097
33	000132
34	000150
35	INACTIVE

-2

-1 kV/m

Figure 39: Contour plot of one-minute averages of KSC field mill readings for 1705 Z on 20 October 1988. The contour pattern around mill #23 is prominent.

been drawn in on a copy of the KSC ∇V contour plot). The contour plots for the other examples of anomalous single mill measurements mentioned above also tend to exaggerate the significance of these other single mill measurements.

The ∇V measured by mill #23 at 1705 Z is seen in proper perspective when plotted as in Fig. 40 where the ∇V value measured by each mill is plotted as a single data point in a simple sequence ordered by the mill site number. The mill #23 measurement is clearly seen to be unique. Another way to display the data which lends some insight into its significance is shown in Fig. 41. In this plot ∇V measured by mill #23 is compared with that measured by the five nearest neighbor mills. The abscissa is the distance in km from mill #23 of mills #21, #22, #25, #29 and #33. The * symbols show ∇V measured by the mills at 1705 Z. The + and x symbols show ∇V values expected at mill sites #21, #22, #25, #29 and #33 if the mill #23 measurement was due to a point charge of 0.1 or 2.75 Coulombs directly over mill site #23 at an altitude of 0.8 or 4.2 km (2,600 or 14,000 ft) respectively. If there were a charge at or above 4.2 km (the 0 °C altitude on this day), it is clear from this plot that the mill #23 measurement would be anomalous since a significant negative measurement of ∇V would be expected at all five nearest neighbor mills. On the other hand, a point charge at 0.8 km, near the altitude which the SPTVAR pilot reported for the cloud tops at about this time, would be expected to influence only mill #23. Although the 1705 Z mill #23 measurement can be explained in this way as due to a small charge directly overhead in the clouds, it is unexpected that a cloud charge would have a lifetime so short that it would appear and disappear between 1700 and 1710 Z at which times mill #23 was measuring fair weather fields in agreement with all the other mills. Thus the 1705 Z mill #23 measurement is still best explained as anomalous.
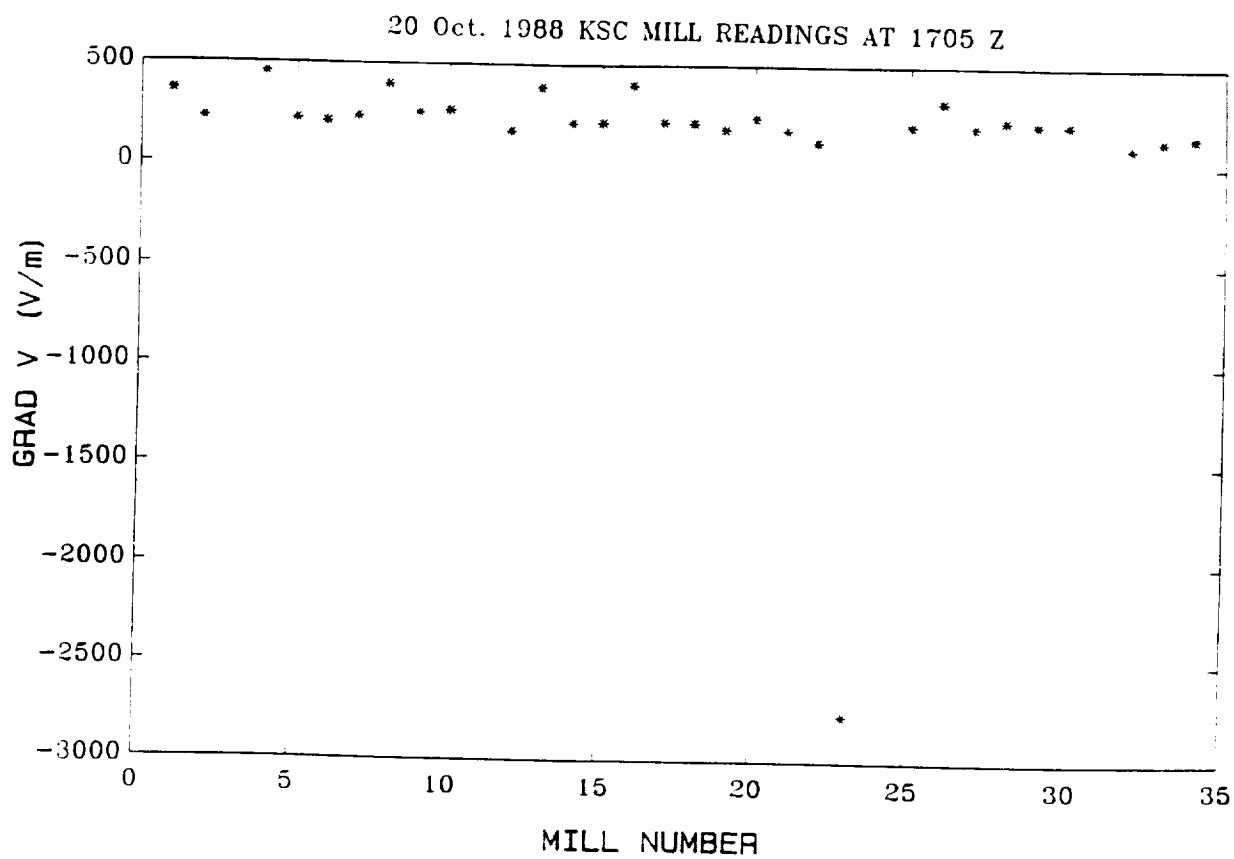
Figure 40: One-minute averages of the electric field measured by the KSC field mills at 1705 Z on 20 October 1988.
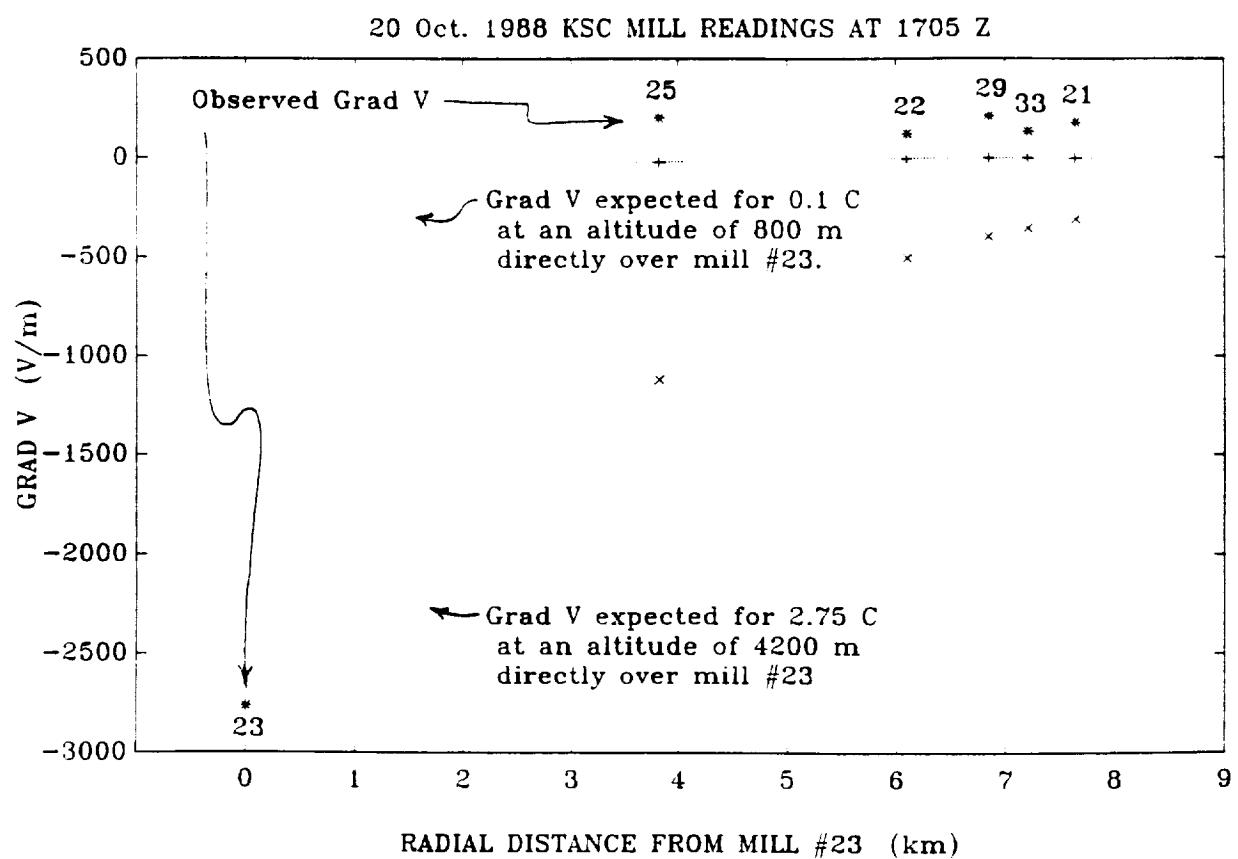
Figure 41: Comparison of the E field at mill #23 with the field at its nearest neighbors at 1705 Z on 20 October 1988. See text for explanation.

D.4 Sea breeze clouds enhanced by outflow boundaries

D.4.1 Summary: 26 September 1988 (88270)

Data for this day were used to check SPTVAR's calibration using a new technique which was suggested by Dr. E. P. Krider of the University of Arizona. The method is this: the electric field change vector ΔE at the ground due to lightning is vertical because of the boundary condition imposed by the horizontal conducting Earth. Furthermore, ΔE changes slowly with altitude in the lowest few kilometers. Thus, when an airplane is flying low over the KSC field mill network, ΔE at its location should be nearly equal to ΔE at the surface as detected by the KSC field mill network.

During the first part of the flight, from 2008 to 2024 Z, SPTVAR was flying at an altitude of 6,000 ft (1.8 km) above sea level over the KSC field mill network in the vicinity of an active thunderstorm. Field changes from lightning are evident in the data from SPTVAR and from the KSC field mills. From the pilot's observations we know that there was a thunderstorm west of KSC and east of Orlando whose anvil extended over KSC. Later in the flight, SPTVAR ascended and entered the bottom of a cloud layer at an altitude of 15,000 ft (4.6 km). The pilot estimated the top to be at 17,000 ft (5.2 km) above sea level with the anvil cloud above.

Earlier in the day, just before SPTVAR's flight, a thunderstorm over Merritt Island west of Port Canaveral had lightning flashes whose polarity indicated the lowering of negative charge to Earth, but during SPTVAR's flight, the flashes consistently indicated the lowering of positive charge. This is unusual. Perhaps the lightning discharged positive charge in the anvil overhead; this is plausible because an hour later, at 2120 Z, one of the authors (J. J. Jones) reported lightning from an anvil over the SPTVAR telemetry trailer at Patrick Air Force Base. An example of multiple lightning flashes in an anvil cloud has been discussed recently by Marshall et al. (1989).

We shall compare the calibration of the surface mills with that of SPTVAR using the flash at 2014:12. At this time SPTVAR was about 1 km south of KSC field mill #10 and was heading northwest as shown in Fig. 42. The vertical component of E at SPTVAR and the field at KSC mill #10 are shown in Fig. 43. Notice that E_z was positive, indicating negative charge overhead, and that the lightning flash at 2014:12 as well as others in this time interval *increased* E_z, indicating a decrease in positive charge overhead. Apparently the field at SPTVAR and at the ground was a superposition of that from several charges, one of which was affected by lightning.
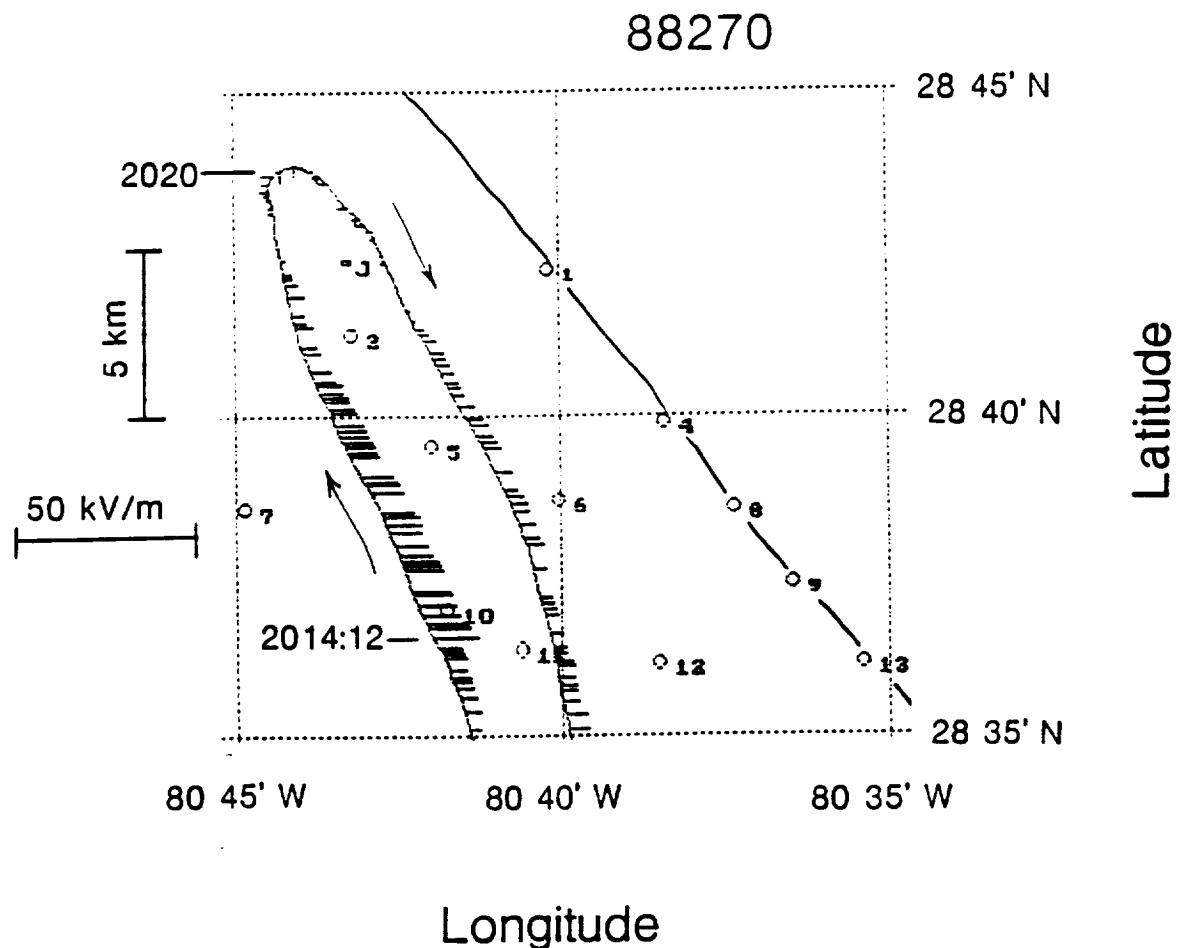
Figure 42: Path of SPTVAR from 2013 to 2026 Z on 26 September 1988. The barbs that jut out to the right of the path have lengths proportional to E_z. The numbered circles show the locations of field mills near the north end of the KSC surface network. The coastline is shown near the easternmost mills.
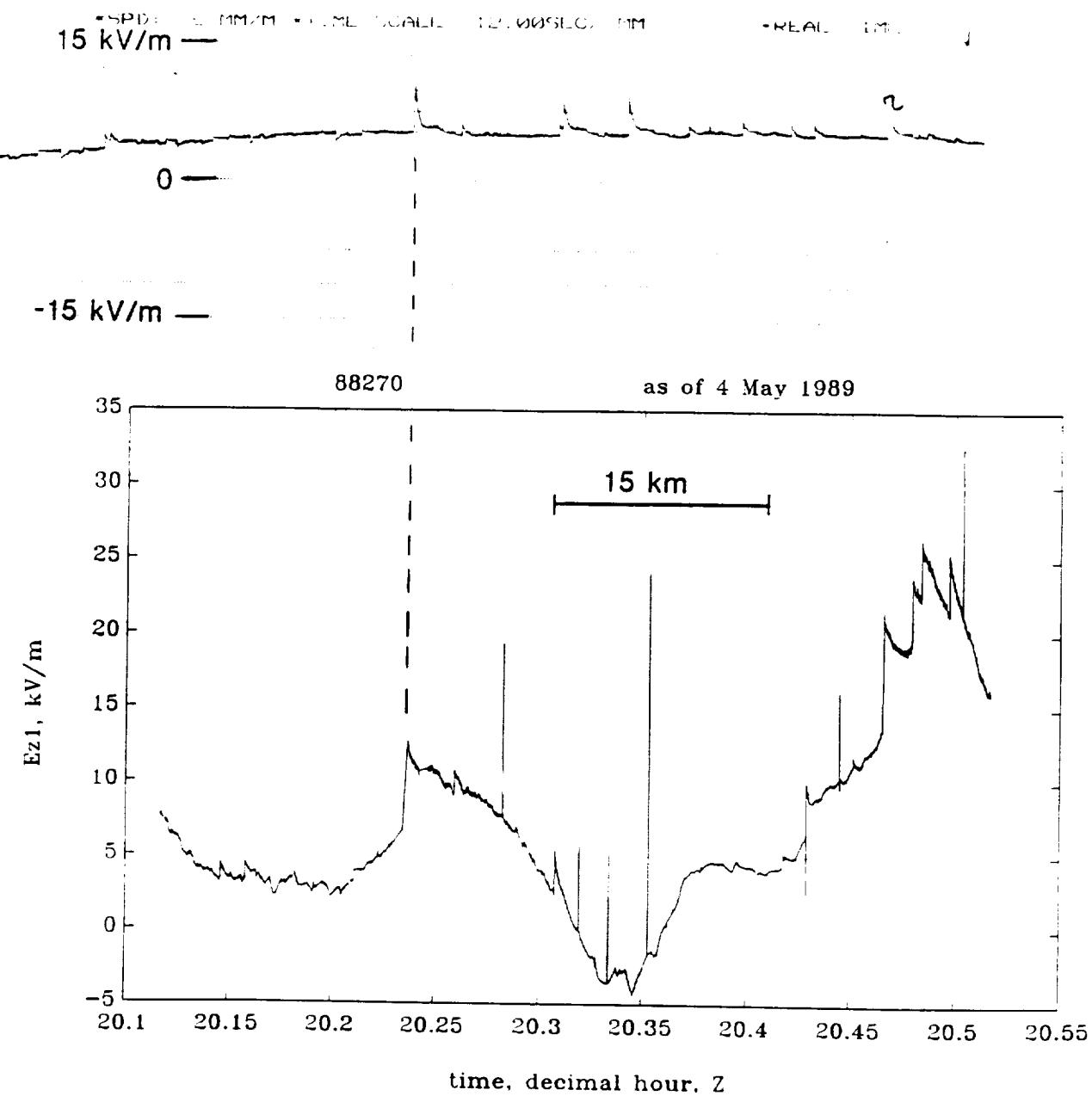
Figure 43: E_Z vs. time at KSC field mill 10 (upper trace) and at SPTVAR (lower trace) on 26 September 1988 from 2006 to 2030 Z. The indicated ΔE due to lightning at 2014:12 (dashed vertical line) is 6.0 kV/m at SPTVAR and 5.6 kV/m at mill 10.

The field changes at 2014:12 were as follows.

$$\Delta E \text{ at SPTVAR} \quad = \quad 6.0 \pm 0.6 \text{ kV/m.}$$
$$\Delta E \text{ at KSC mill } \#10 \quad = \quad 5.6 \pm 0.2 \text{ kV/m.}$$
$$\Delta E \text{ at KSC mill } \#11 \quad = \quad 5.4 \pm 0.2 \text{ kV/m.}$$

The estimate of uncertainties for SPTVAR come from an analysis of a calibration we obtained by flying SPTVAR beside a captive balloon. The uncertainties for the surface mills are simply based on the precision with which we could estimate distances on the strip chart records made at the Cape Canaveral Forecast Facility. The differences between ΔE at SPTVAR and at the surface mills are well within the estimated uncertainties.

The field change ΔE will be nearly the same at two locations provided the distance between them is much less than the distance from either location to the region of charge affected by lightning. Since ΔE has the same polarity over the entire KSC network of field mills, the lightning at 2014:12 may have been a cloud-to-ground flash. To estimate the location of the charge affected by this flash, we constructed a model consisting of a single point charge and its image charge and varied the magnitude and location of the charge to best fit the electric field changes at the surface. Figure 44 shows a comparison of ΔE calculated from the model with that measured at the surface. The agreement is only fair. ΔQ has a magnitude of -160 C and is located 6 km west of the field mill network at an altitude of 59,000 ft (18 km). The altitude is probably too high to be realistic (the anvil cloud appeared to be at a lower altitude), and the magnitude of ΔQ is correspondingly large. Large errors in the model are to be expected because our measurements of ΔE were taken from strip chart records whose time resolution is much too low to resolve the field changes due to individual return strokes and leaders. However, the model does tell us that the region of charge affected by lightning was far from SPTVAR and mill #10. Therefore, ΔE at SPTVAR should have been very nearly equal to that at mill #10.
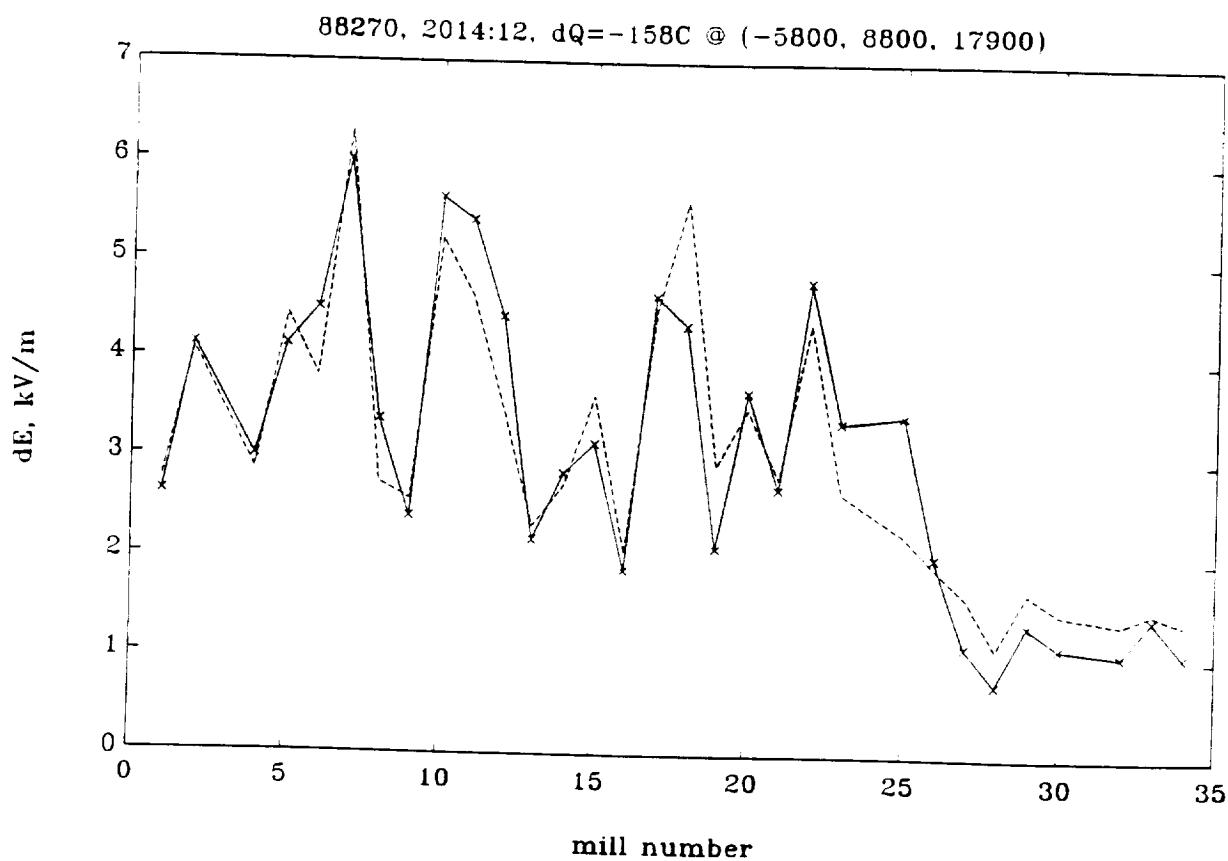
Figure 44: ΔE at 2014:12 on 26 September 1988 at the KSC surface field mills. Solid line: measured values. Dashed line: values calculated from the discharge of -158 C at a location 5.8 km to the west of the field mill network at an altitude of 18 km.

D.4.2 Summary: 27 September 1988 (88271)

This day's flight was initiated to study cumulus clouds beginning to grow over KSC/CCAFS behind a thunderstorm which formed over the south gate of CCAFS at about 1630 Z. This storm had passed south of PAFB by the time of SPTVAR's 1715 Z takeoff. However, the clouds over Patrick were still electrified and electric fields to $+40$ kV/m were measured by SPTVAR as soon as it was airborne. SPTVAR flew north and by the time it entered the CCAFS area it was out of the area influenced by these clouds. The entire flight was at 6,000 ft (1.8 km) altitude. The flight track of SPTVAR is shown in Fig. 45.

Between 1800 Z and 1900 Z a few cumulus formed, one of which moved in over Launch Complex 39 and made a rain shower. No significant electric field associated with these clouds was detected by SPTVAR, although a very weak field of a few hundred V/m was measured by the KSC field meter network on the surface.

Later in the flight SPTVAR made four passes under an electrified anvil extending over the south end of Mosquito Lagoon from a storm toward Orlando. E_Z to -5.8 kV/m was measured by SPTVAR and a few flight maneuvers were made for calibration purposes. Plots of the two-dimensional vectors E_{XY} and E_{XZ} at intervals along the SPTVAR flight track for the four passes are shown in Figs. 46, 47, 48 and 49.

The upper panels (a) in these figures show the two horizontal components, E_Y and E_X, of the electric field vector plotted at intervals along the track of SPTVAR. Each two-dimensional vector, although plotted in the aircraft reference frame, is also the correct projection of the electric vector on the horizontal plane in geodetic space. The divergence of the E_{XY} vectors in each of the plots indicates that they are pointing away from positive charge(s) located at the geometric origin(s) of the vectors. The origin points of the E_{XY} vectors, represented here by the $+$ symbols enclosed by circles, thus indicate the approximate latitude and longitude of the source charges.

The lower panels (b) in these figures show the z and x components of the electric vector similarly plotted along the track of the airplane. In these plots, however, the vertical component of the field, E_Z, is plotted horizontally and the component in the direction of flight, E_X, is plotted along the flight track. The divergence of the vectors in these plots confirms the positive nature of the source charges deduced from the E_{XY} plots. The vertical position of a charge symbol in a E_{XZ} plot indicates the latitude of the charge only approximately. However, the distance of a symbol to the right of the flight track indicates the approximate height of the charge above the airplane flight altitude.

Thus, these plots provide estimations of the latitude, longitude and altitude of charge concentrations in the anvil below which SPTVAR flew. These plots indicate that the charge in the anvil was somewhat spread out in a north-south direction along the SPTVAR flight track since E_Y was generally small compared to E_Z. Indeed multiple charge locations are
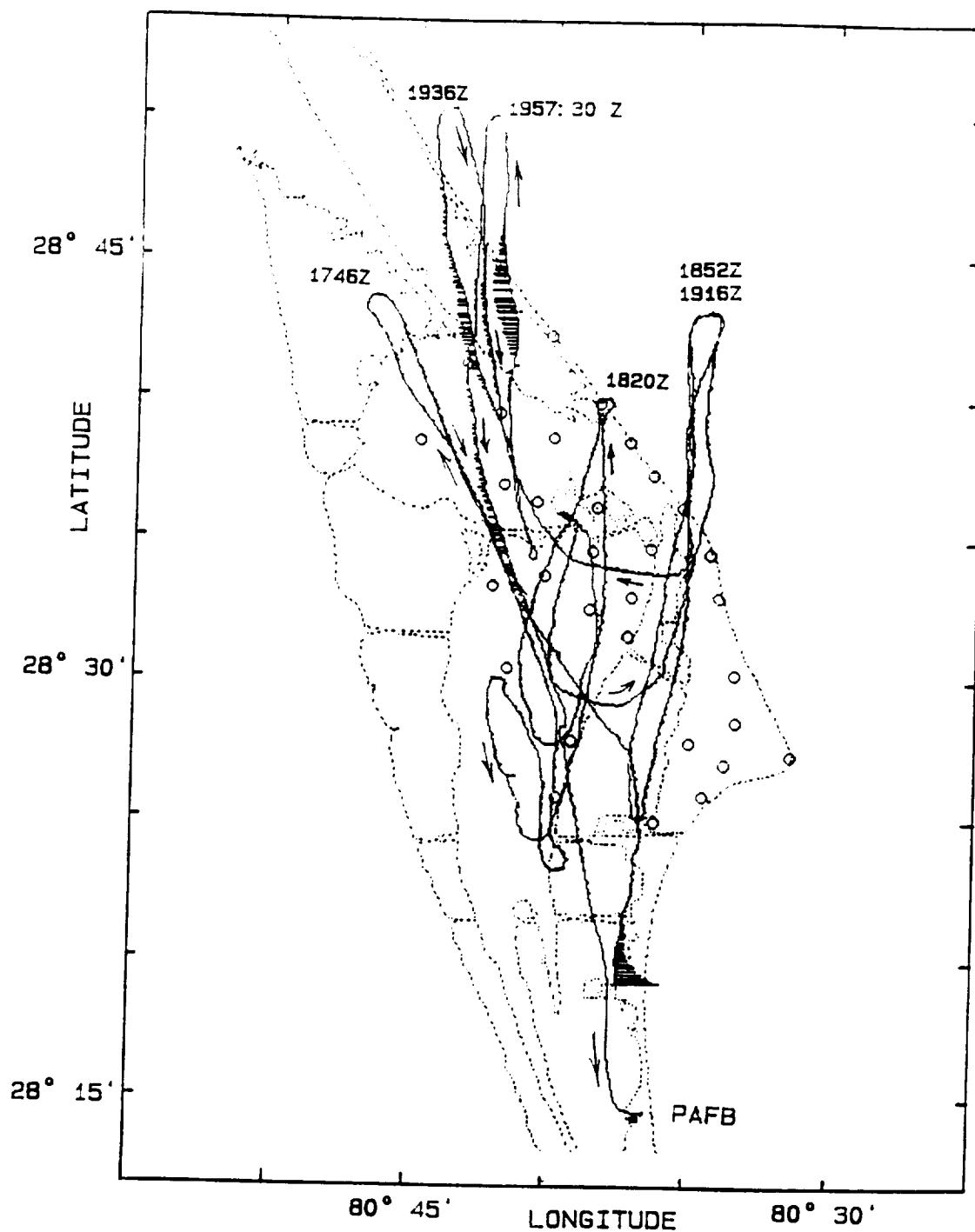
Figure 45: The SPTVAR flight track for 27 September 1988. SPTVAR departed Patrick AFB under the north edge of a declining thunderstorm. E_Z to -40 kV/m was measured on departure, but the KSC area was free of fields at 6,000 ft (1.8 km) until SPTVAR began flying under an anvil from a distant storm at about 1930 Z. E_Z to -5.8 kV/m was measured under the anvil.
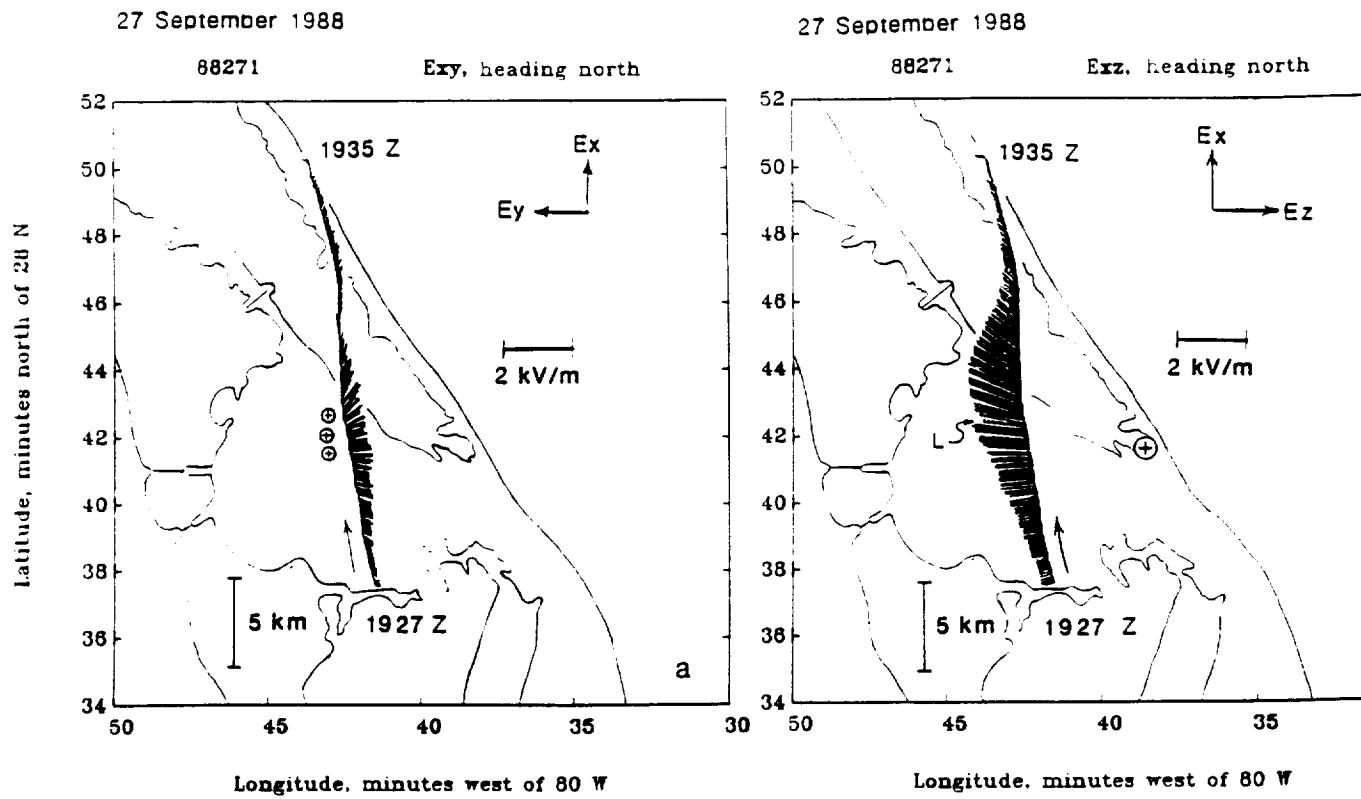
Figure 46: E_{XY} vectors (a) and E_{XZ} vectors (b) along the SPTVAR flight track for the first below anvil pass on 27 September 1988. Approximate charge locations are shown by the + symbols enclosed by circles. In panel a the positions of these symbols indicate the approximate latitude and longitude of the charges, while in panel b the vertical positions of the symbols indicate the approximate latitude of the charge while the distances of the symbols to the right of the track indicate the height of the charges above the airplane flight altitude of 6,000 ft (1.8 km). The abrupt change in the pattern in panel b at the point marked by L indicates a reduction in the charge overhead due to a lightning flash.

90

27 September 1988

88271   Exy, heading south

27 September 1988

88271   Exz, heading south
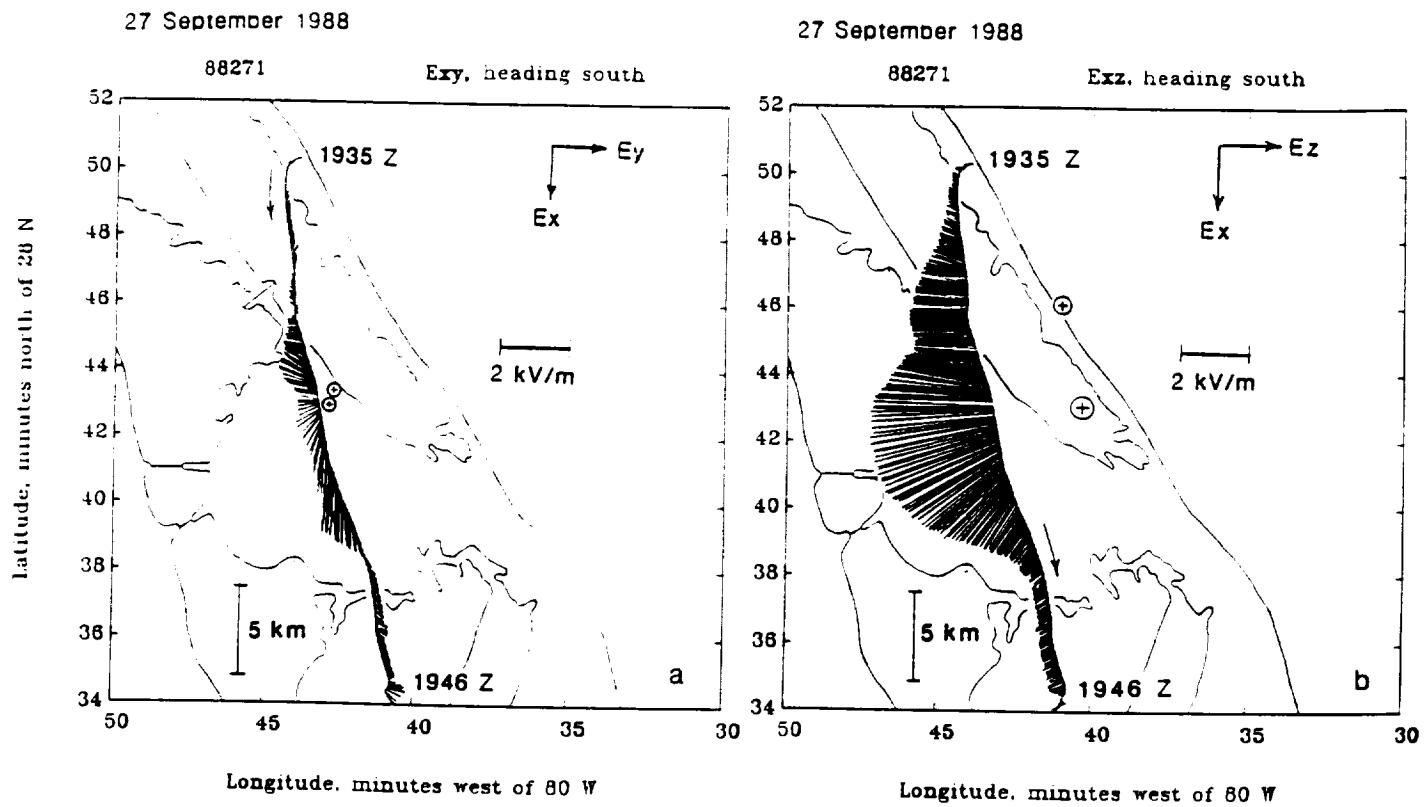
Figure 47: E_{XY} vectors (a) and E_{XZ} vectors (b) along the SPTVAR flight track for the second below anvil pass on 27 September 1988. Approximate charge locations are shown by the + symbols enclosed by circles. In panel a the positions of these symbols indicate the approximate latitude and longitude of the charges, while in panel b the vertical positions of the symbols indicate the approximate latitude of the charge while the distances of the symbols to the right of the track indicate the height of the charges above the airplane flight altitude of 6,000 ft (1.8 km).

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resolvable for all four passes in the E_{XY} plots, and indicate charge locations horizontally close to the airplane track. Note, however, that the charge locations labeled c in Figs. 48 and 49 coincide with a small active cloud that SPTVAR penetrated at the indicated place along its track. This cloud was about 2,000 ft (0.6 km) thick on the third pass and about 4,300 ft (1.3 km) thick on the last pass. The plots indicate that this cloud contained a small positive charge just above the SPTVAR altitude.

The closely spaced charges resolved in the E_{XY} plots are not resolved in the E_{XZ} plots since they were farther away vertically than horizontally from SPTVAR. Panel a of Fig. 47 locates a second charge north of the larger one over the south end of Mosquito Lagoon. This second charge is not identified in the E_{XY} plot in panel b, indicating that it was located directly above the flight track. The abrupt change in the pattern of the E_{XZ} vectors at Lin panel b of Fig. 46 at about 1930:20 Z indicates a lightning flash. Since the change in E_X and E_Y was small while that in E_Z was about 20%, the charge must have been removed from the anvil nearly directly above SPTVAR.

The skew T diagrams for the 12 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 50.
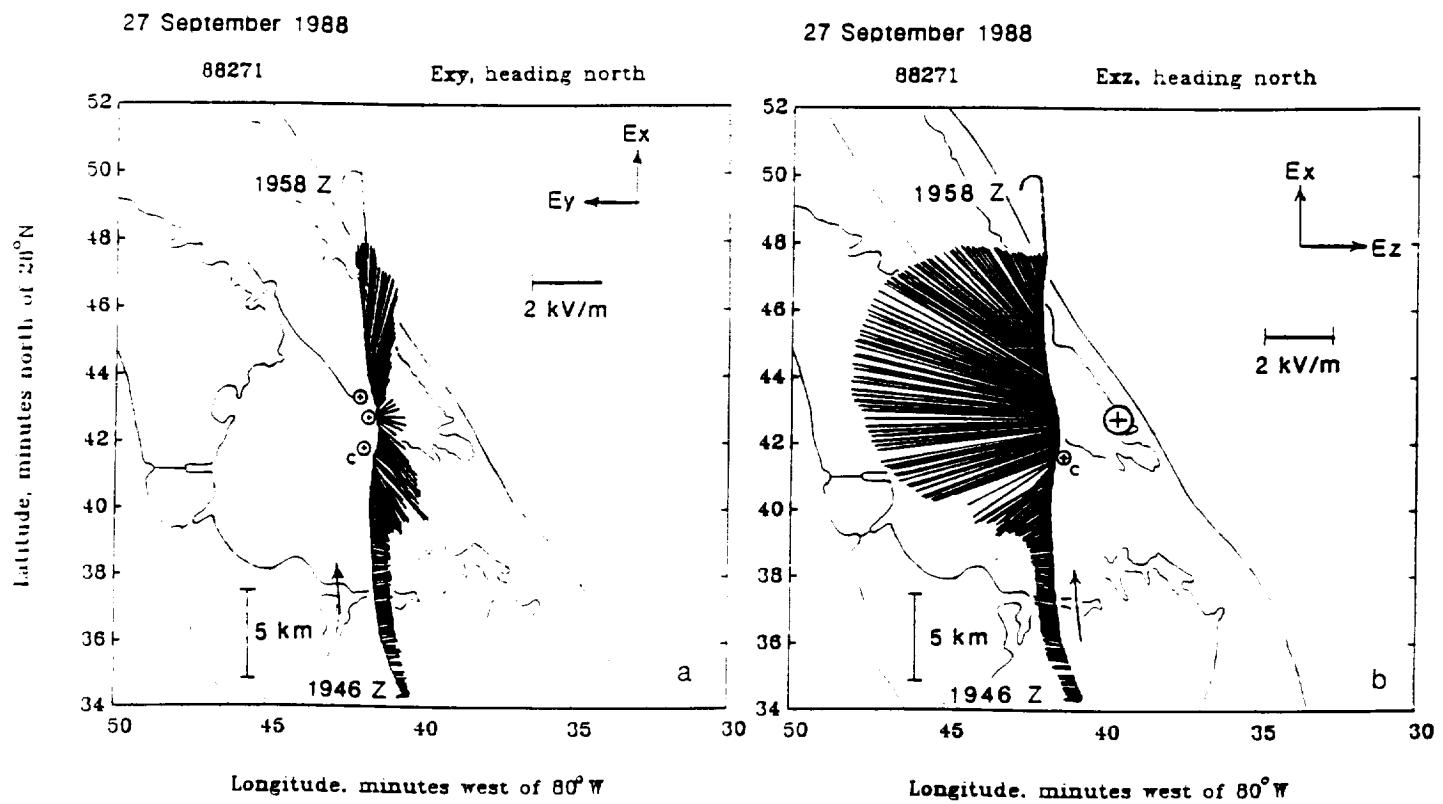
Figure 48: E_{XY} vectors (a) and E_{XZ} vectors (b) along the SPTVAR flight track for the third below anvil pass on 27 September 1988. Approximate charge locations are shown by the + symbols enclosed by circles. In panel a the positions of these symbols indicate the approximate latitude and longitude of the charges, while in panel b the vertical positions of the symbols indicate the approximate latitude of the charge while the distances of the symbols to the right of the track indicate the height of the charges above the airplane flight altitude of 6,000 ft (1.8 km).

93
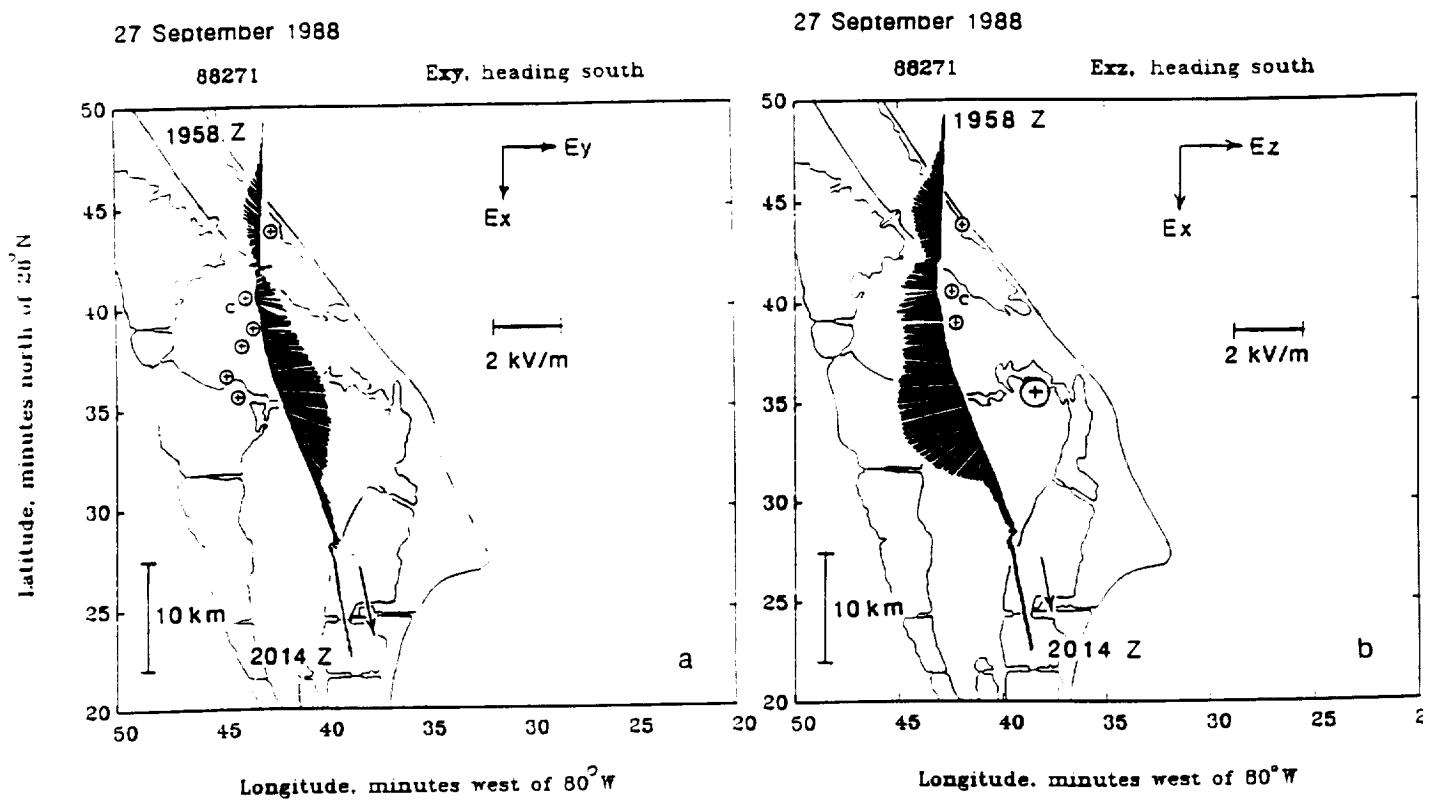
Figure 49: E_{XY} vectors (a) and E_{XZ} vectors (b) along the SPTVAR flight track for the fourth below anvil pass on 27 September 1988. Approximate charge locations are shown by the + symbols enclosed by circles. In panel a the positions of these symbols indicate the approximate latitude and longitude of the charges, while in panel b the vertical positions of the symbols indicate the approximate latitude of the charge while the distances of the symbols to the right of the track indicate the height of the charges above the airplane flight altitude of 6,000 ft (1.8 km).

94
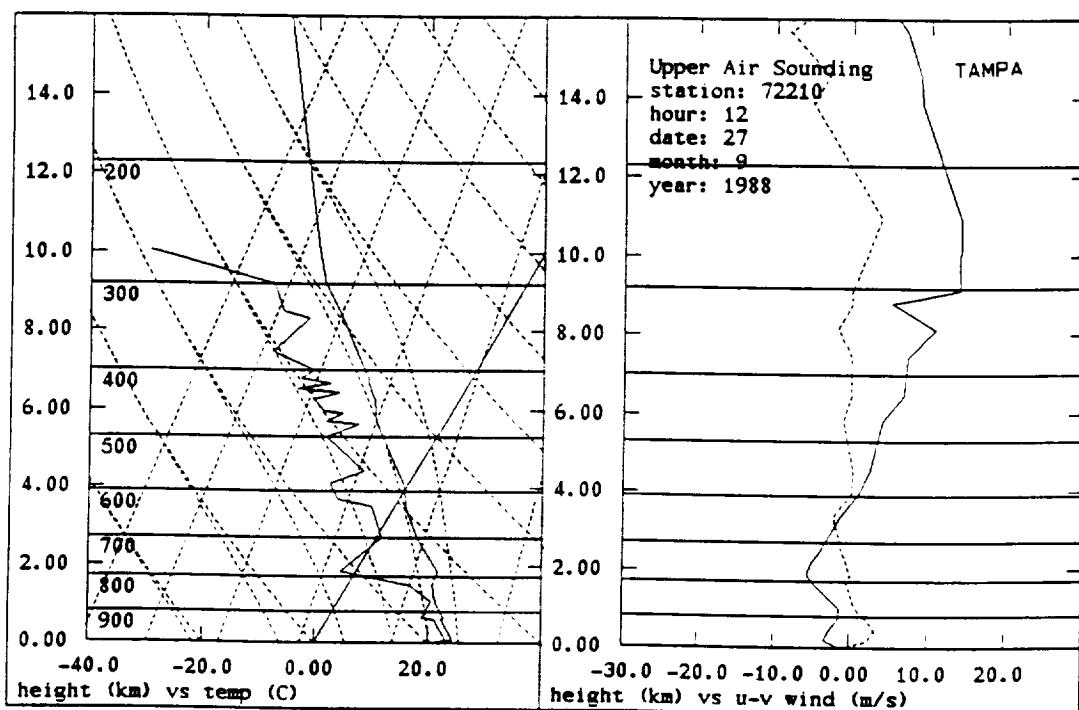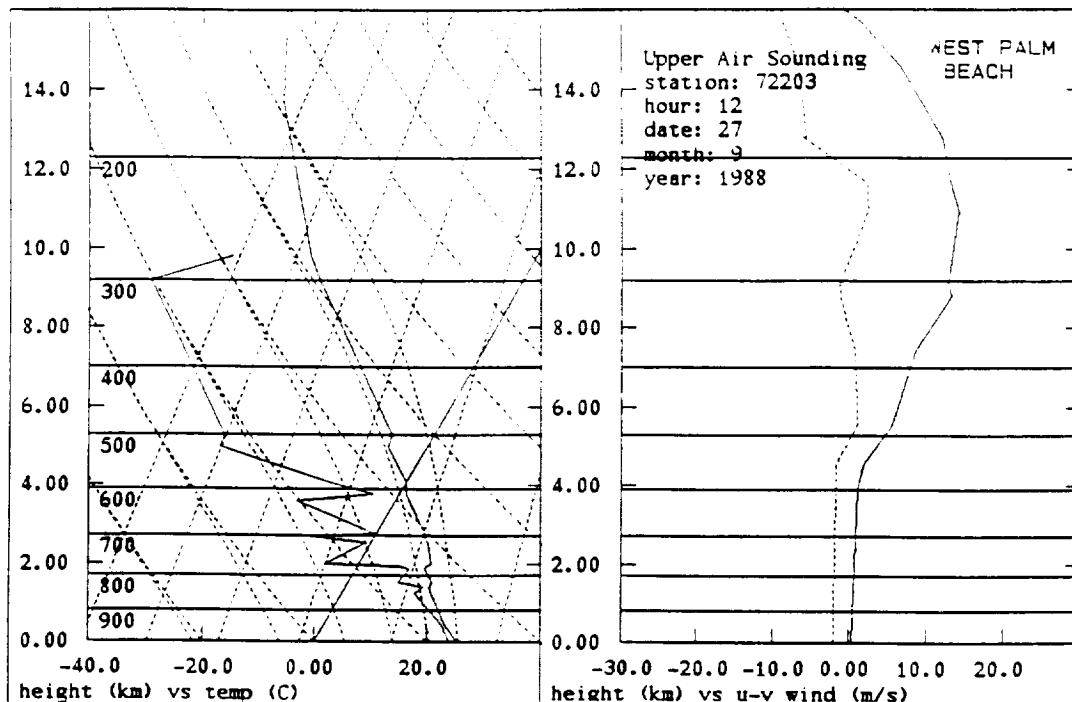
Figure 50: 27 September 1988 West Palm Beach and Tampa, Florida, skew T diagrams. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

D.4.3 Summary: 17 October 1988 (88291)

This day's flight began when a third cycle of convection was beginning over KSC. Unlike the earlier cycles which were shorter and more uniformly convective, this one involved layers of cloud moving in from the ocean with embedded convective features. The SPTVAR flight track for this day is shown in Fig. 51.

The first cloud studied was over the Banana River adjacent to Port Canaveral and moved rapidly south out of the restricted area. The KSC E-field contour plots indicate that from 1720 to 1725 Z KSC mill #33 reported a ∇V of about -330 V/m due to this cloud. The second cloud studied was over the north end of CCAFS. SPTVAR had to break off study of this cloud at about 1800 Z when it moved too close to restricted area R2931. At 1750 the McGill radar showed echo tops to 25,000 ft (7.6 km), above the $-20\,°$C level at 23,000 ft (7 km), for this second cloud studied. The KSC field mill network reported only fair weather electric fields over the entire network at this time (but see below).

The final cloud studied was over the east shore of Merritt Island and drifting slowly west. It was the most vigorous cloud of the day with strong vertical winds and heavy rain at the SPTVAR's altitude of 5,000 to 6,000 ft (1.5 to 1.8 km). Panel c of Fig. 52 shows the LWC measured in cloud penetrations during the period 1800–1900 Z.

The measured LWC values were some of the largest measured with SPTVAR, and produced the strong charging of the airplane shown in panel b. In the E_Z plot shown in panel a the noisier intervals are correlated with intervals of SPTVAR charging and are the result of plumes of electric charge being emitted consequent to the strong charging of the airplane by the LWC.

For most of the time interval shown E_Z was about -100 V/m , with an excursion to slightly more negative values between 1818 and 1830 Z (18.3–18.5 Z in Fig. 52). This apparent small atmospheric electric field reached its largest value of about minus two hundred volts per meter at about 1826Z (18.43Z in Fig. 52). Each data point in Fig. 52 results from analysis of averaged field mill data. An average of the eight field mill measurements in 0.5 s time intervals was calculated before the airplane charge field (E_{Qz}) and E_Z were calculated. This reduced the amplitude of the noise in E_Z and E_{Qz} due to the charge plumes but did not affect the contributions due to the ambient atmospheric field.

During this time (1818–1830 Z) SPTVAR made three passes, south, north, and southbound over the KSC Headquarters area and along a path extending from just northeast of mill #17 to a point over the Banana River between mills #23 and #29. Neither mill #17 nor mill #20, the two closest KSC mills, reported other than fair-weather electric fields during this time interval. Indeed, during the time interval from 1730 to 1900 Z the original KSC strip chart records show that the KSC field mills were all reporting fair-weather fields except for a brief excursion of a few minutes duration for four mills as follows. Mill #23
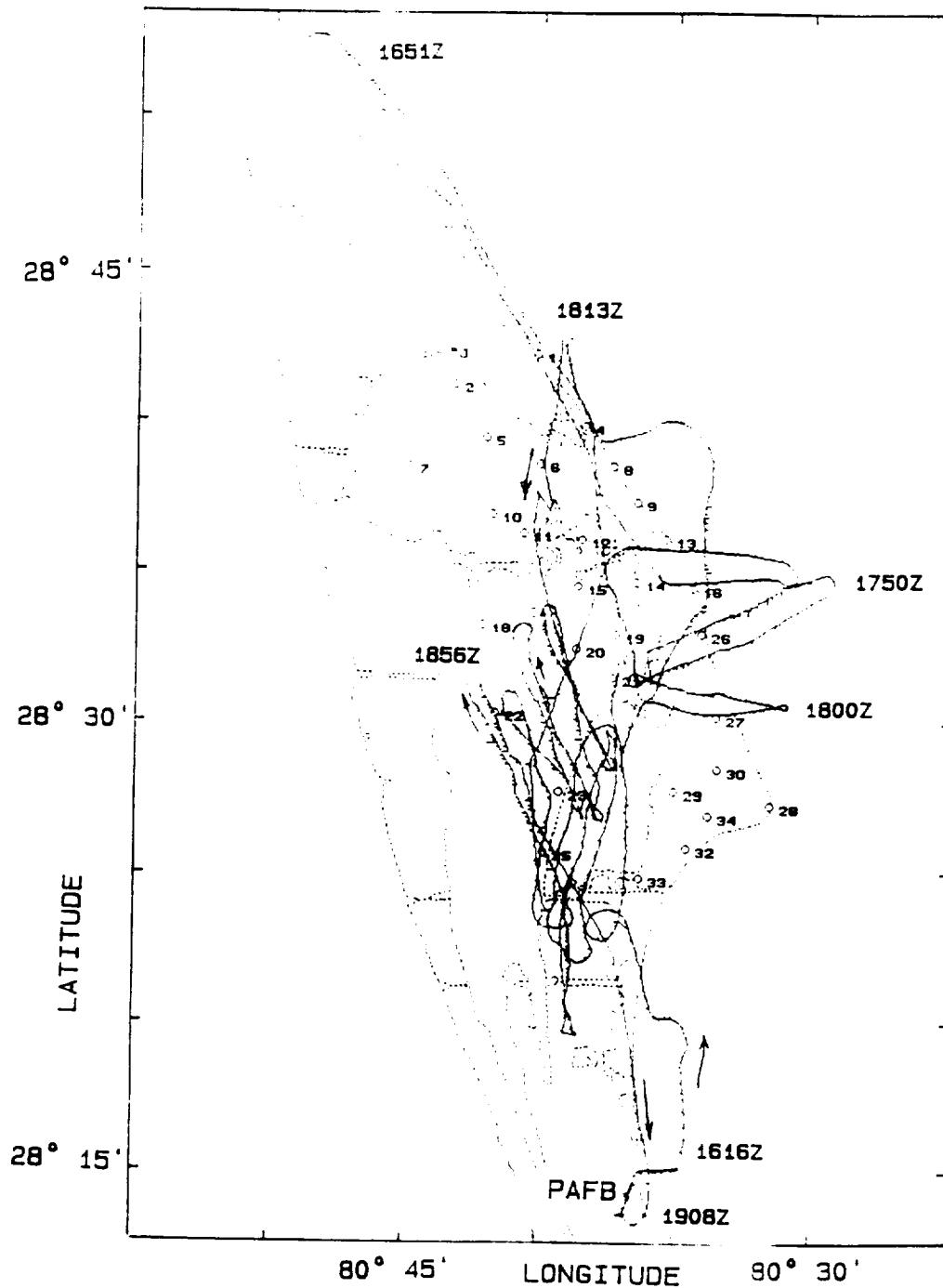
Figure 51: The 17 October 1988 SPTVAR flight track. The largest field measured on this flight was about -250 V/m over Merritt Island near mill #17. The threshold for E_Z barbs in this figure is 0.1 kV/m and a barb of length 1 mm represents a field magnitude of 400 V/m.

97
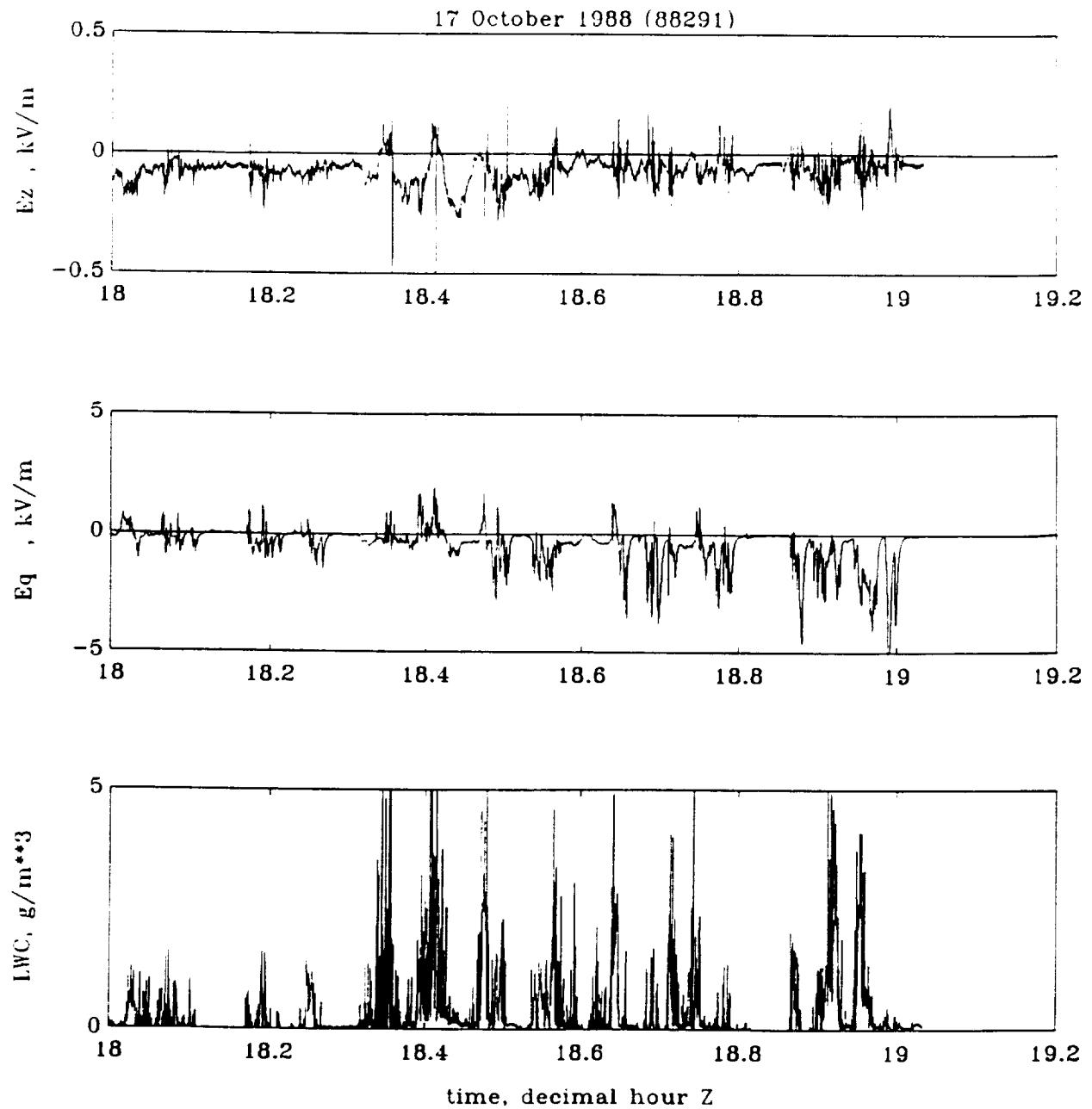
Figure 52: E_Z, airplane charge-field E_q and LWC for 1800–1900 Z on 17 October 1988. The largest field measured on this flight was the excursion of E_Z to -250 V/m at 18.43 Z (1826 Z) when SPTVAR was near mill #17.

to −400 V/m at 1800 Z, mill #25 to −750 V/m and mill #34 to +400 V/m at 1805 Z and mill #30 to −200 V/m at 1845 Z. The resolution of the original strip chart records is about ±200 V/m. SPTVAR was not near any of these mills when they were reporting these excursions. The negative readings of mills #23 and #25 may have been due to a part of the second cloud studied by SPTVAR after the main part of the cloud, with radar tops to 25,000 ft as noted above, moved too close to restricted area R2931.

On this day there was abundant moisture to 9,000 ft (2.7 km), above which the relative humidity was 20%. The wind was northeasterly up to 13,000 ft (4 km). Skew T diagrams for the 0 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 53.
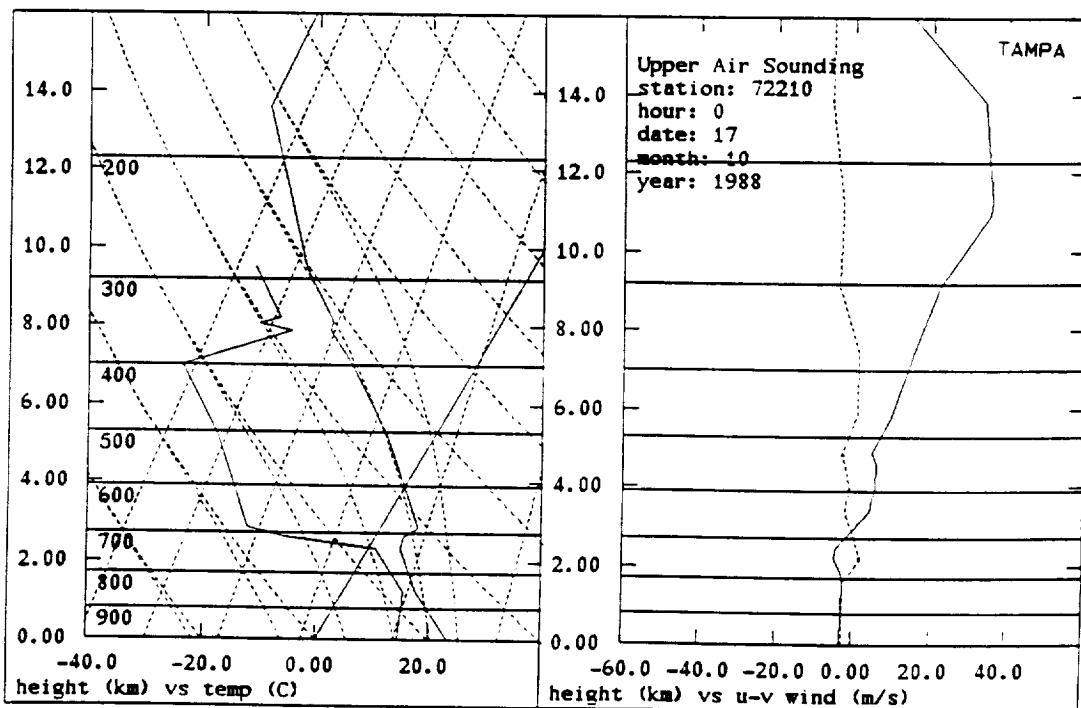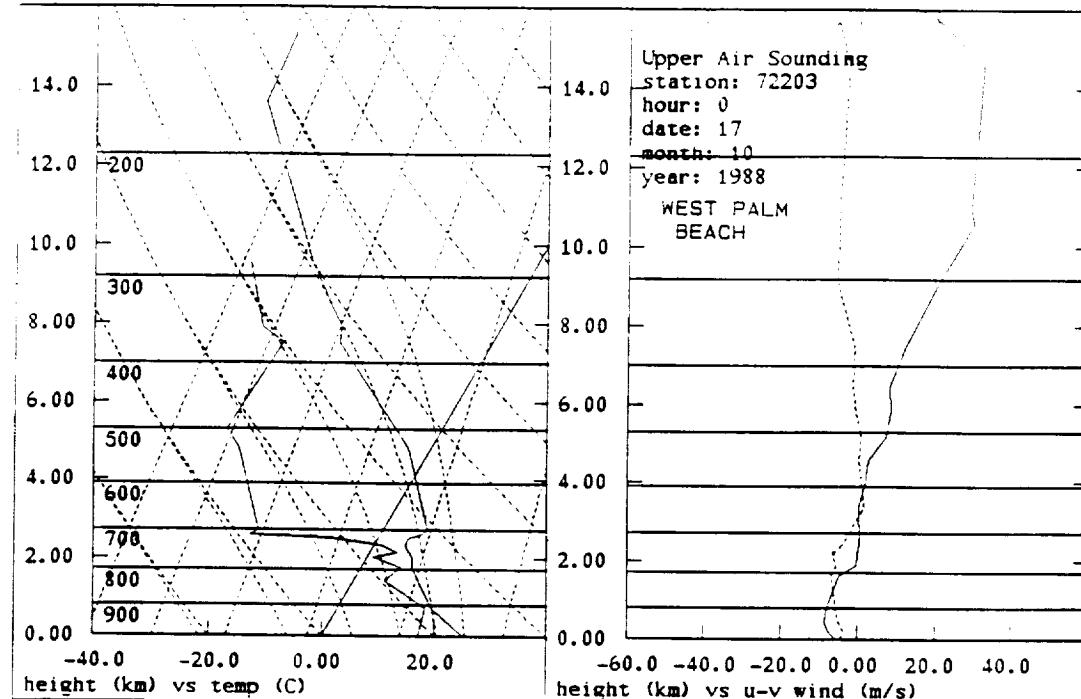
Figure 53: Skew T diagrams from the 0 Z West Palm Beach (A) and Tampa, Florida, (B) soundings on 17 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

100

D.5 Clouds in an easterly flow enhanced by an upper level short wave

D.5.1 Summary: 18 September 1988 (88262)

The electric field strength at the surface exceeded 1 kV/m at various times and locations from 1540 Z until after 1755 Z. At 1625 Z the field rose to 5500 V/m at mill #17 as SPTVAR flew over it. There was very little lightning over the field mill network during this time. Around 1727, when $|E| < 1$ kV/m, some small changes in E may have been caused by distant lightning; surface observations at Cape Canaveral Forecast Facility indicate thunder and rain showers at 1726 Z.

The clouds were layered with embedded convective cells. SPTVAR flew over and just west of the KSC field mill network from 1617 to 1801 Z, initially at 10,000 ft (3 km) altitude, then ascending to 17,000 ft (5.2 km) later in the flight to ascertain the cloud top height of 17,000 ft. The airplane encountered significant electric fields in the vicinity of embedded convective cells.

The most intense field at SPTVAR (100 kV/m) was at 1722:24 Z, near the northwest corner of the KSC field mill network in a strongly convective cloud, probably a thundercloud, although there is no evidence of lightning from the electric field measurements at SPTVAR. The nearest KSC mills, #2 and #7 (located, respectively, about 12 and 10 nmi from the SPTVAR position), recorded no significant field at this time and so could not provide any conclusive lightning signature had lightning occurred. SPTVAR was at 17,000 ft (5.2 km) above sea level. The field at KSC mill #2 exceeded 1 kV/m at about 1731 and KSC mills #5, #6, and #10 exceeded that value about 20 minutes later.

The electric field from the cell that SPTVAR flew through around 1624 shows up well at the surface (see Fig. 54), but the change in polarity at the surface is not evident at SPTVAR's altitude (Fig. 55).

This flight was undertaken to study layered clouds, but the electrical activity encountered by SPTVAR was associated with embedded convective cells. Electric field measurements by SPTVAR and the KSC surface mills yield consistent locations for the electrified cells.

STATIC CONTOUR

MINUTE VOLTS/METER
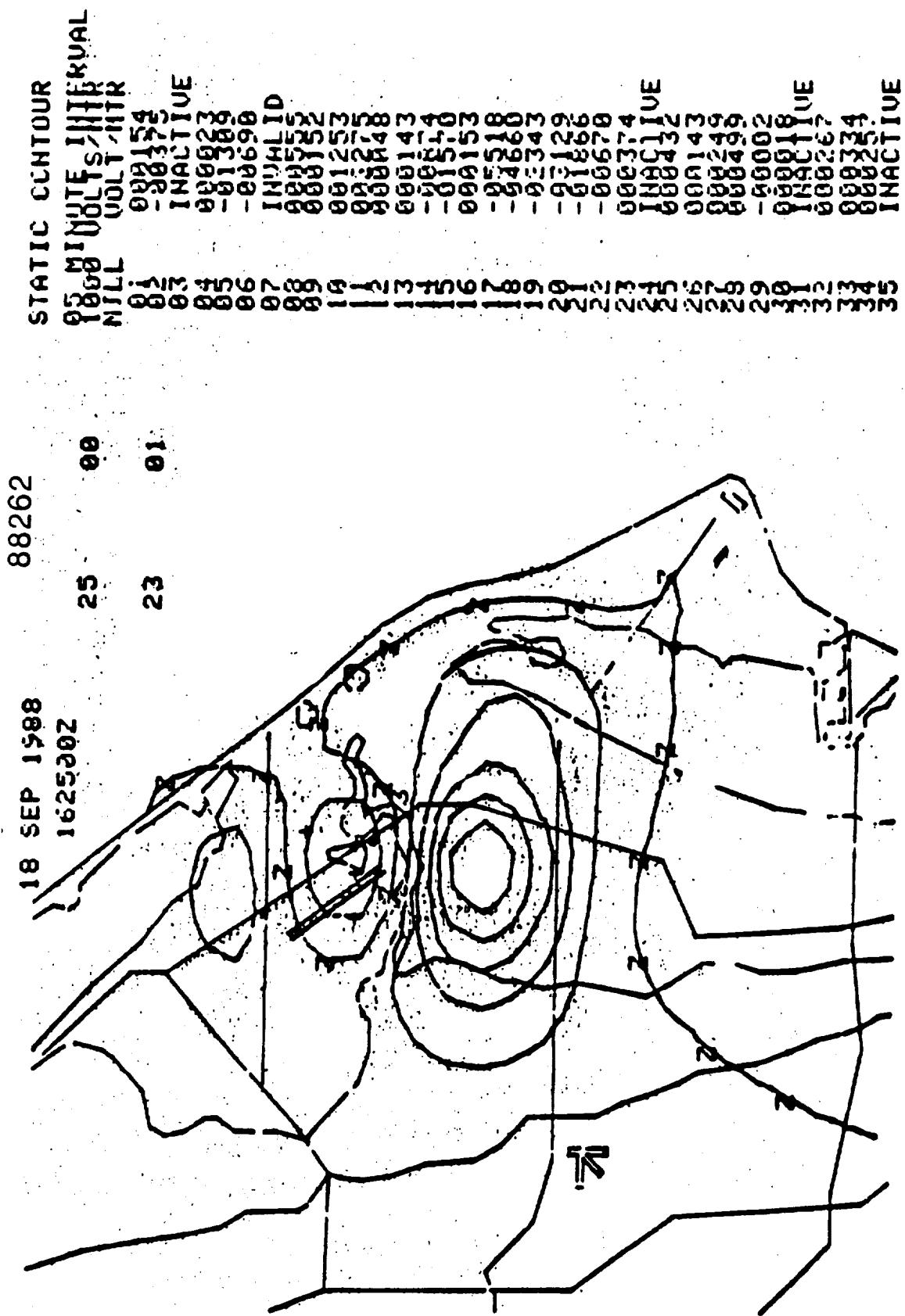
Figure 54: Electric field contours at the surface in the vicinity of KSC at 1625 Z on 18 September 1988 (88262). The contour with Z's along it is 0 V/m. The contour interval is 1 kV/m. The maximum value of E is -5.5 kV/m at KSC mill #17.
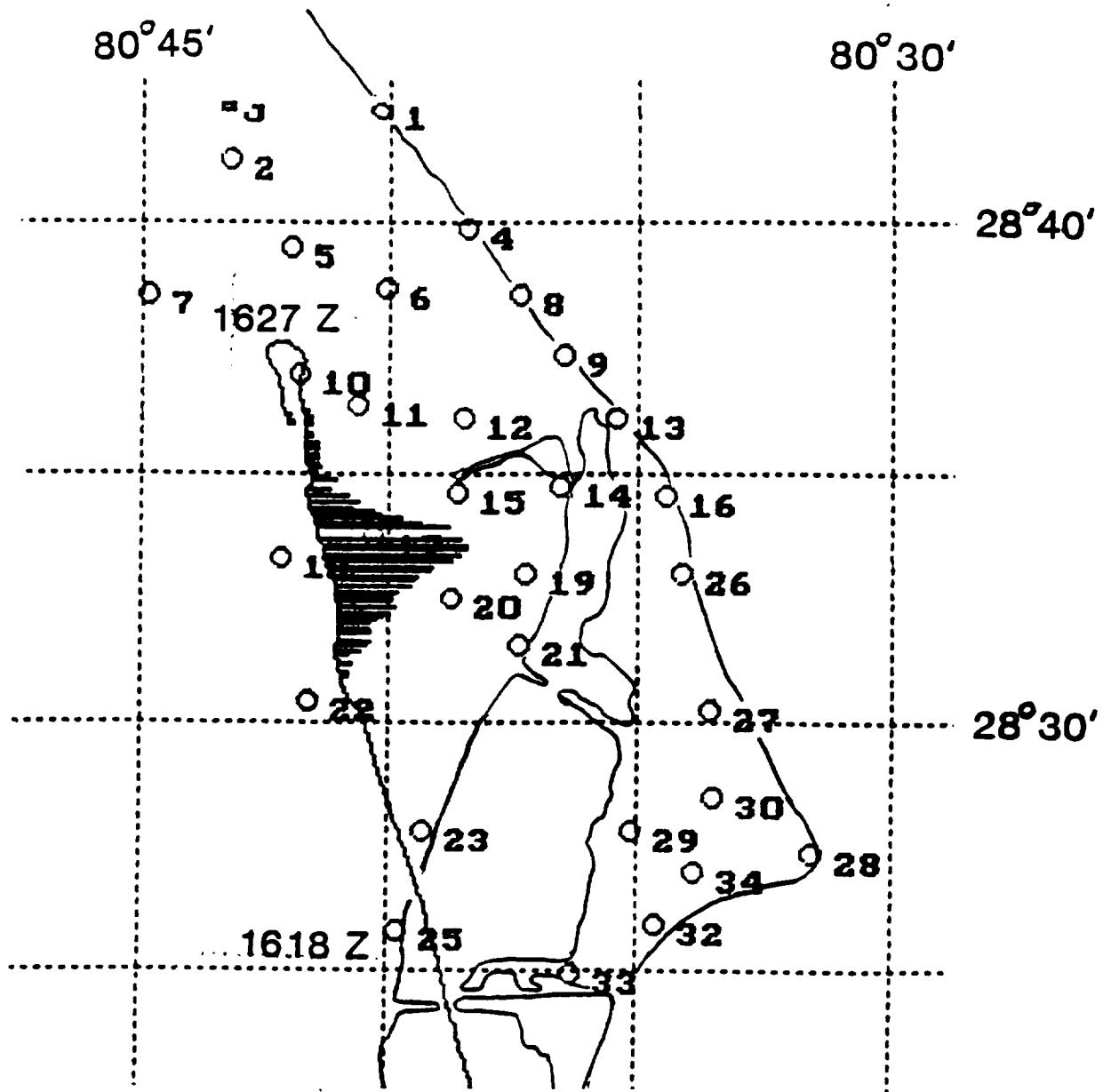
Figure 55: Vertical component of E along SPTVAR's track from 1618 to 1627 Z on 18 September 1988. The horizontal lines that jut out to the right of SPTVAR's track have lengths proportional to E_z, which reached a maximum value of 24 kV/m at 1624:20 Z when SPTVAR was over KSC mills #17 and #18. The circles with numbers show the locations of KSC field mills. The coastline and the shores of the Banana River also are shown. The dashed lines show latitude and longitude at 5-minute intervals.

D.5.2 Summary: 31 October 1988 (88305)

The objective of this day's flight was to study cumulus clouds moving on-shore as part of an east-west convergence line which remained over the Cape all morning between the CCAFS Industrial Area and the Port. The radar showed that this line remained stationary while individual echoes moved toward the west. The strongest convection remained offshore all day. The sounding was very moist with relative humidity in excess of 70% to 16,000 ft (5 km), and greater than 30% from there to 26,000 ft (8km). The stability indices supported a potential for convection and lightning. [The skew T diagrams for the 12 Z West Palm Beach and Tampa, Florida, soundings are shown in Fig. 56.]

SPTVAR flew from 1304 to 1558 Z, mostly at 6,000 ft (1.8 km). The flight track for this flight has been presented earlier in this report as Fig. 3 and again in Fig. 4 with E_Z barbs along the track. This was a most interesting flight, both for its demonstration of a new approach to operational use of SPTVAR for studying electrified clouds (see Section 5), and for the interesting picture obtained of the electrical structure of the clouds (see Section 6).

Since the plot of the horizontal E vector, $\vec{E}_{XY}$, along its path (Fig. 7) indicated cloud charges near SPTVAR, it is of interest to compare the airplane $\vec{E}$ data with the cloud reflectivity measured by the McGill Radar at Patrick AFB. Figure 57 shows the deduced horizontal electric vector along the SPTVAR's flight path overlaid on a contour plot of radar reflectivity (a 2 km CAPPI from the McGill radar). The contours shown are those of 25, 35, 40 and 45 dBZ, at an altitude of 2 km, just above the SPTVAR flight altitude. Other than the charge labeled a in Fig. 7, all the charge locations are within or near the 25 dBZ contour.

A calculated RHI through the cloud at about the longitude of the easternmost pass shown in Fig. 57 is presented in Fig. 58. In this figure the SPTVAR path with E_Z barbs plotted along it is superimposed on 5, 20, 35 and 40 dBZ reflectivity contours. The two prominent E_Z maxima were not coincident with the highest reflectivities, but rather just outside the 35 dBZ contours, under depressions in the top of the 20 dBZ contour. It is interesting that in this cloud the detected charges were in relatively low reflectivity regions, indicating that cloud regions with radar reflectivities as low as 20 dBZ may harbor considerable charge accumulations.

Although substantial fields were measured at the surface and by SPTVAR, there was no indication in the electric field records or from the lightning location system that lightning was associated with the clouds in the CCAFS/KSC area on this day. However, the SPTVAR measurements suggest that the clouds moving in over the Cape may have been capable of sustaining a triggered lightning flash, had a launch vehicle ascended through them.
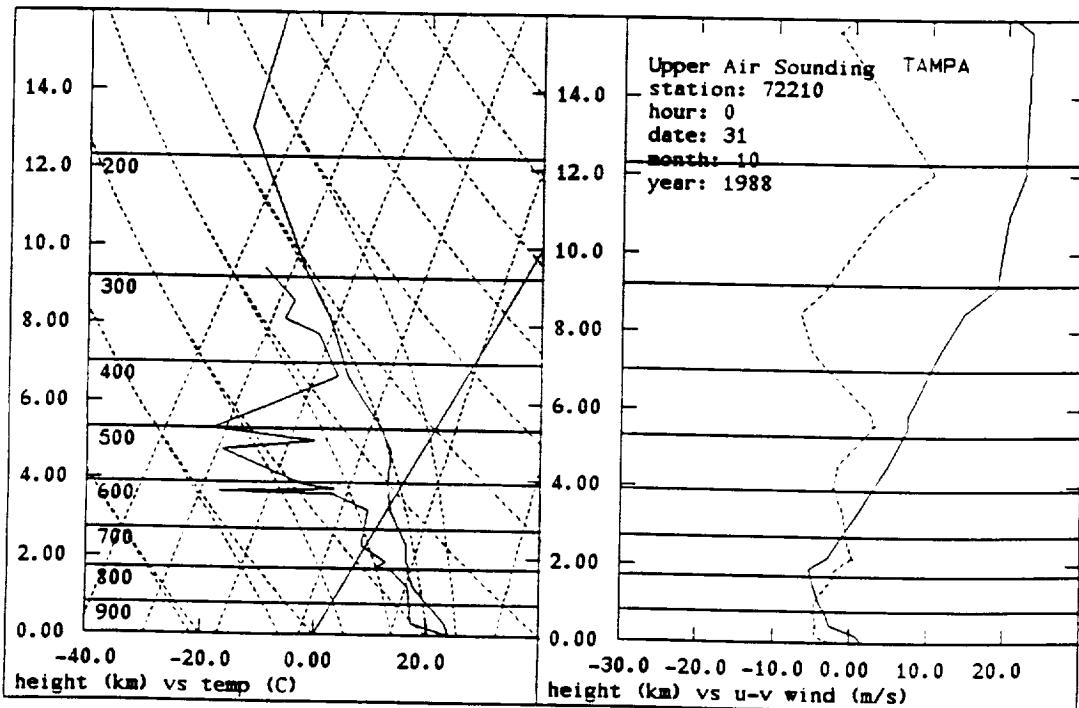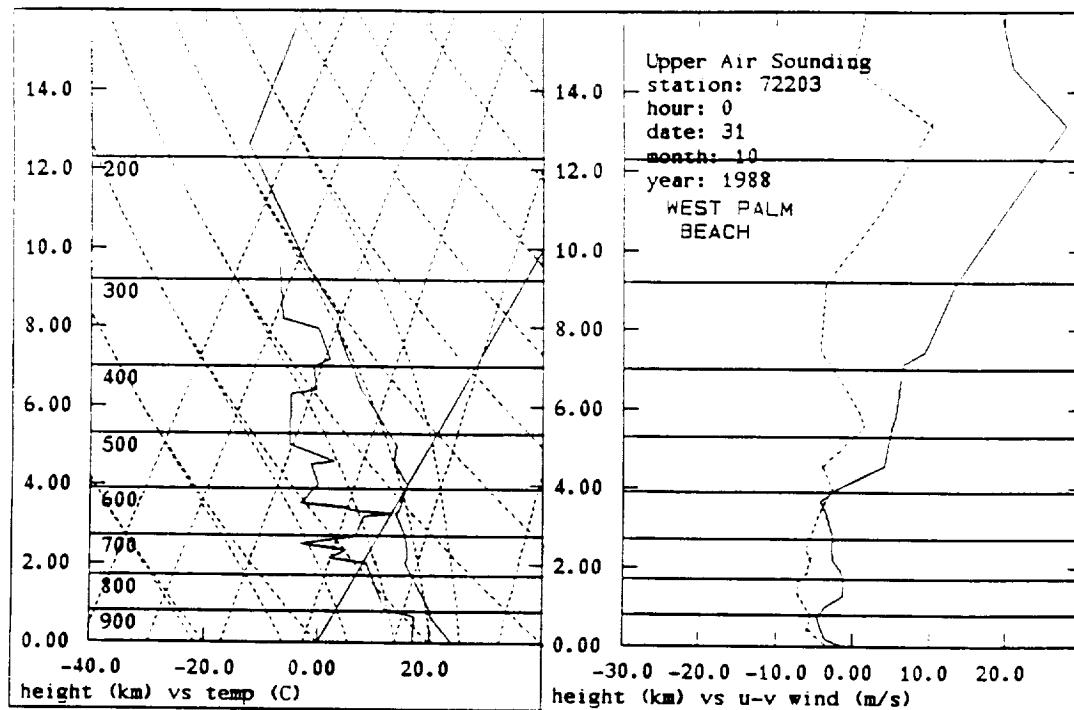
Figure 56: The skew T diagrams for the 12 Z West Palm Beach (A) and Tampa, Florida, (B) soundings on 31 October 1988. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

105
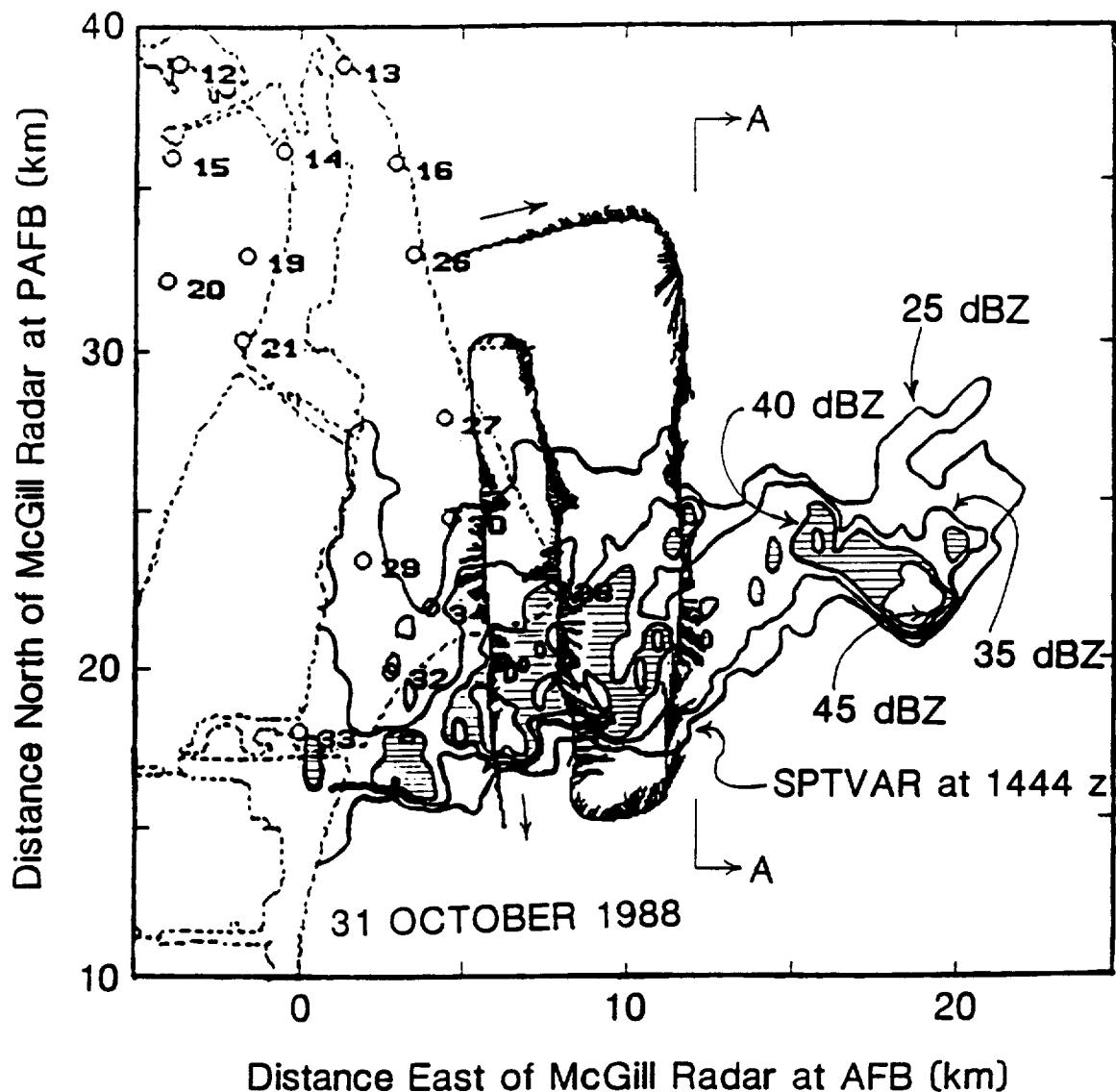
Figure 57: 31 October 1988 McGill radar CAPPI at 2 km overlaid with the SPTVAR track and $\vec{E}_{XY}$ barbs. The CAPPI represents the time interval 1444–1449 Z while the flight track shown was from 1436 to 1457 Z. A–A represents the position of the calculated RHI shown in the next figure.
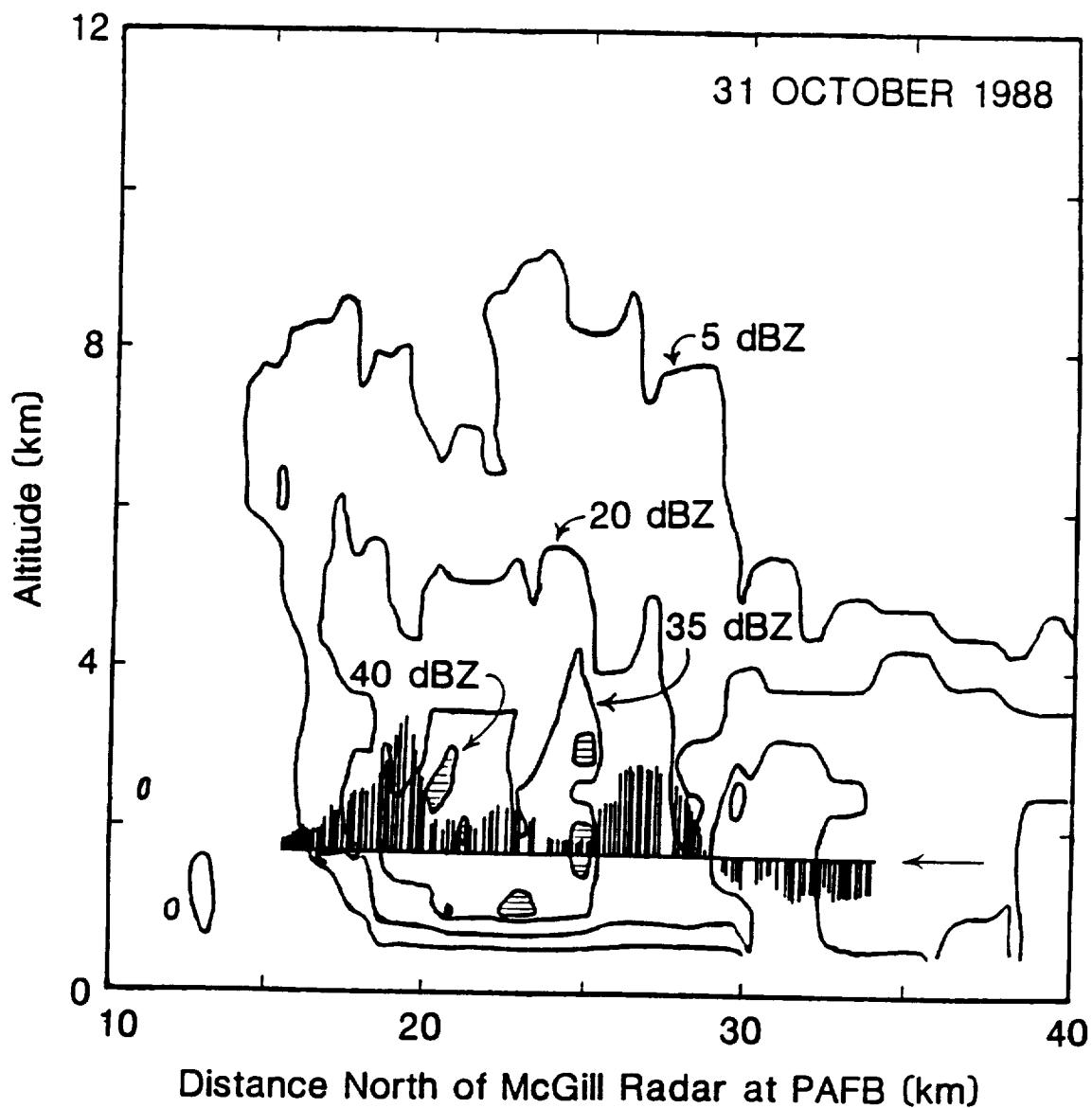
Figure 58: 31 October 1988 McGill radar calculated RHI at SPTVAR longitude overlaid with the SPTVAR track and E_Z barbs. The RHI represents the time interval 1444–1449 Z, while the flight track shown was from 1439 to 1445 Z.

D.6 Layered Clouds with Westerly Winds

D.6.1 Summary: 1 November 1988 (88306)

The object of this day's flight was to study clouds that formed a solid overcast. SPT-VAR climbed slowly to 6,000 ft (1.8 km) through a lower cloud layer between 1,000 and 1,600 ft (0.3 and 0.5 km) and a second layer extending from just above the first one to about 2,300 ft (0.7 km). SPTVAR flew for two hours and measured only fair weather fields throughout the flight. The flight track is shown in Fig. 59.

D.6.2 Summary: 4 November 1988 (88309)

On this day, the surface mills indicated a more intense electric field than SPTVAR did flying directly over them. This is unusual. This day's flight is discussed as a case study in Part II of this Final Report.
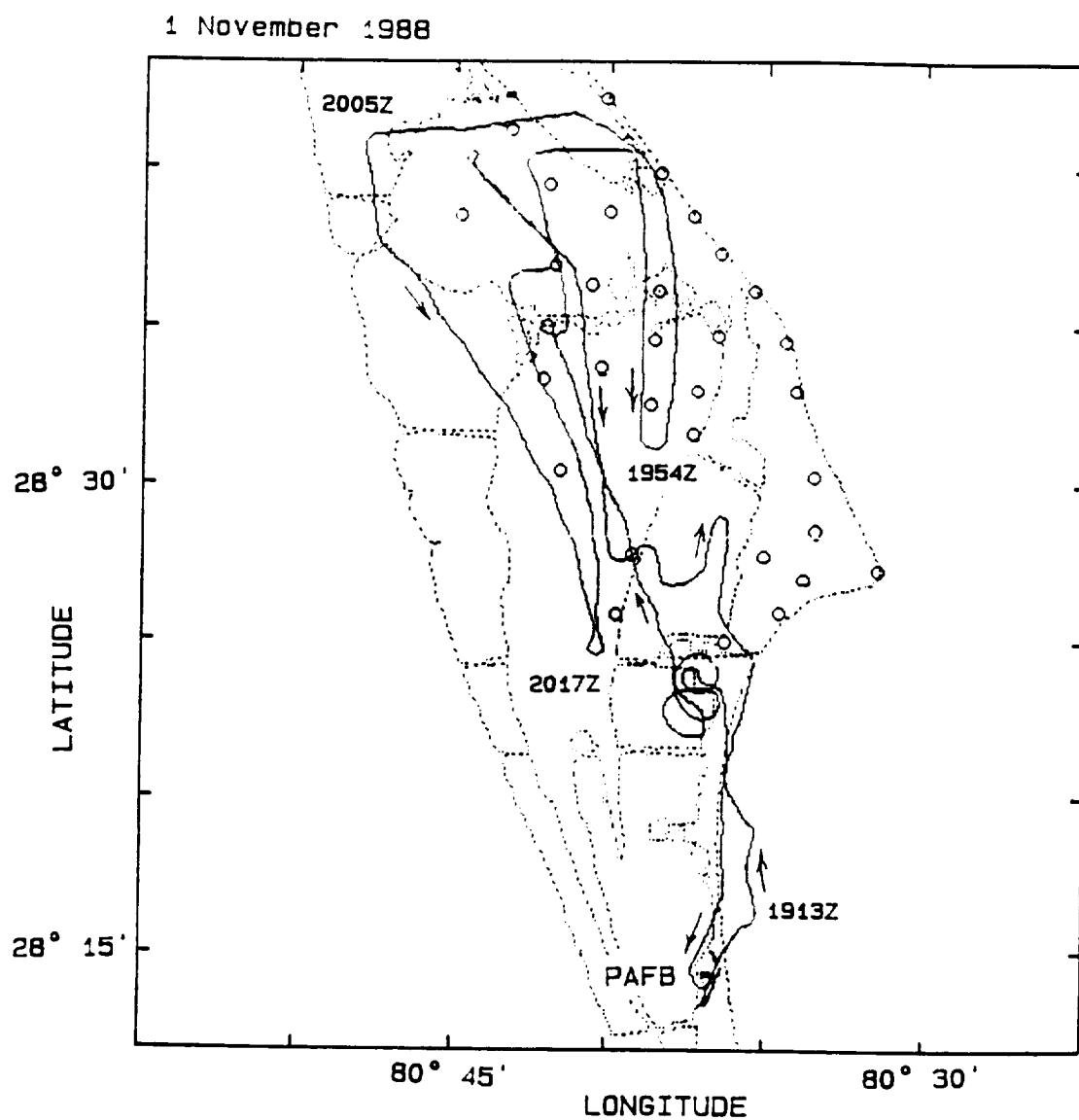
1 November 1988

Figure 59: The 1 November 1988 SPTVAR flight track. Only fair weather fields were measured on this flight.

Aircraft Measurements of Electrified Clouds
at Kennedy Space Center

Final Report: Part II
Case Study: 4 November 1988 (88309)

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April 27, 1990

1 Introduction

Part of the mission of the Airborne Field Mill Project during the fall of 1988 was to investigate electrified clouds that might pose a hazard to operations at Kennedy Space Center. In this part of the Final Report we present a case study for a flight over KSC on November 4, 1988 (88309). This flight was chosen for two reasons.

- The clouds were weakly electrified, and no lightning was reported during the flight.

- Electric field mills in the surface array at KSC indicated field strengths greater than 3 kV/m, yet the SPTVAR aircraft flying directly over them at an altitude of 3.4 km above sea level measured field strengths less than 1.6 kV/m.

2 Weather Summary

Ms. Launa Maier summarizes the weather on November 4, 1988, in the following way.

There was a high-amplitude, long-wave trough extending from central Canada through the Midwest, through the Mississippi River Valley and into the Gulf of Mexico. There were high winds in excess of 100 knots on both sides of the long wave trough. At 500 mb several short waves were present. One extended from southern Mississippi and Alabama and was expected to affect Florida's weather. The shortwave trough had moved across the Southwest two days ago and had maintained a large pocket of moisture throughout its journey.

At 0600 Z the entire peninsula of Florida was under cloud cover. The area of tallest echoes extended along a line from Fort Myers to just south of Cape Canaveral and offshore to the northeast. Echo movement was from 220 degrees at 10 knots. A tornado was reported in the Fort Myers area during the early morning hours. At approximately 1040 Z, two lightning flashes were observed over the KSC area. By 1200 Z most of the activity was south of PAFB. Another line started forming from Tampa to just south of Jacksonville. As the line passed through the area later, there were light rainshowers but no significant convection.

The morning sounding was moist from the surface through 500 mb. The winds were southwesterly all the way up. The convective temperatures were in the mid and upper 70's and the K-indices exceeded 30 throughout the southern part of the state. The stability indices had sharp gradients between central and northern Florida. The Peninsula was in a very stable environment.

The aircraft flew from approximately 1215 to 1530 Z. The plane ascended and passed through the first cloud base at 11,300 ft at approximately 1300 Z. The tallest echoes were over CCAFS and the Port and were predominantly layered clouds. AT 1440 Z the aircraft was flying in the vicinity of light rainshowers near Field Mill Site 5. The aircraft charged but did not detect any fields other than fair weather. The aircraft headed home about 1515 Z.

At 1125 Z the field mill display system (specifically the ARMS buffer) was brought back on line after repair. Prior to that time, the contour plots have values which are not representative of the atmospheric electric field. The strip chart records were not affected by the downtime of the display. After preliminary examination it appears that the digital data are accurate after 1125 Z, but the contour algorithm was not enabled until after 1300 Z. The eastern and central field mills measured fields in excess of 3 kV/m between 1105 Z and 1150 Z. Starting at approximately 1300 Z the CCAFS field mills began crossing over to negative fields. Fields on the order of −4 kV/m were reached before they dissipated about 1330 Z. By 1350 Z all fields were less than 1 kV/m with the exception of Field Mill 4. Field mill 4 measured a −1 kV/m field. After 1440 Z all the mills measured fields less than 1 kV/m.

The 500 mb chart is shown in Fig. 1. A trough extending south of Mississippi is evident.

Figure 2 shows an infrared satellite photograph of the northern half of Florida at 1331 Z. KSC is under the western edge of the extensive area of cloud cover at the right side of the photograph.

Notice that Ms. Maier uses the potential gradient convention for the sign of the electric field: $\nabla V = -E$ is positive when positive charge overhead dominates. We shall use the opposite convention, that E is positive when it exerts an upward force on a positive charge (i.e., when there is a negative charge overhead).

3   Soundings

Figures 3 and 4 show soundings at Key West, West Palm Beach, and Tampa, Florida, and Waycross, Georgia. All the soundings were at 1200 Z on 4 November 1988, and they support the weather summary above. The winds were from the southwest and the air was very moist from the surface up to a small inversion around 500 or 600 mb.
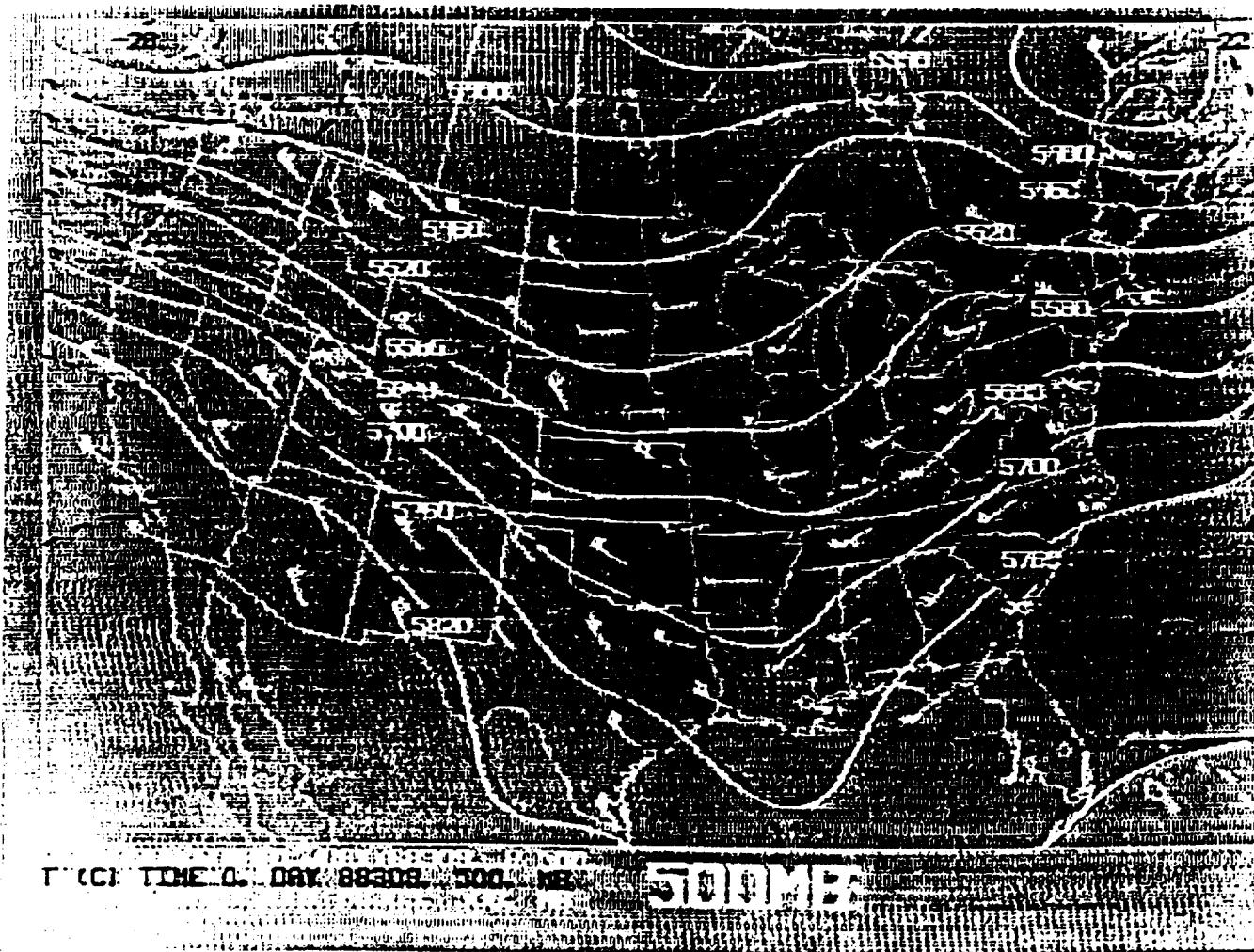
Figure 1: 500 millibar chart at 1200 Z on 88309.

Figure 2: Goes-7 Satellite photograph for 88309, 1331 Z, showing northern and central Florida.

4
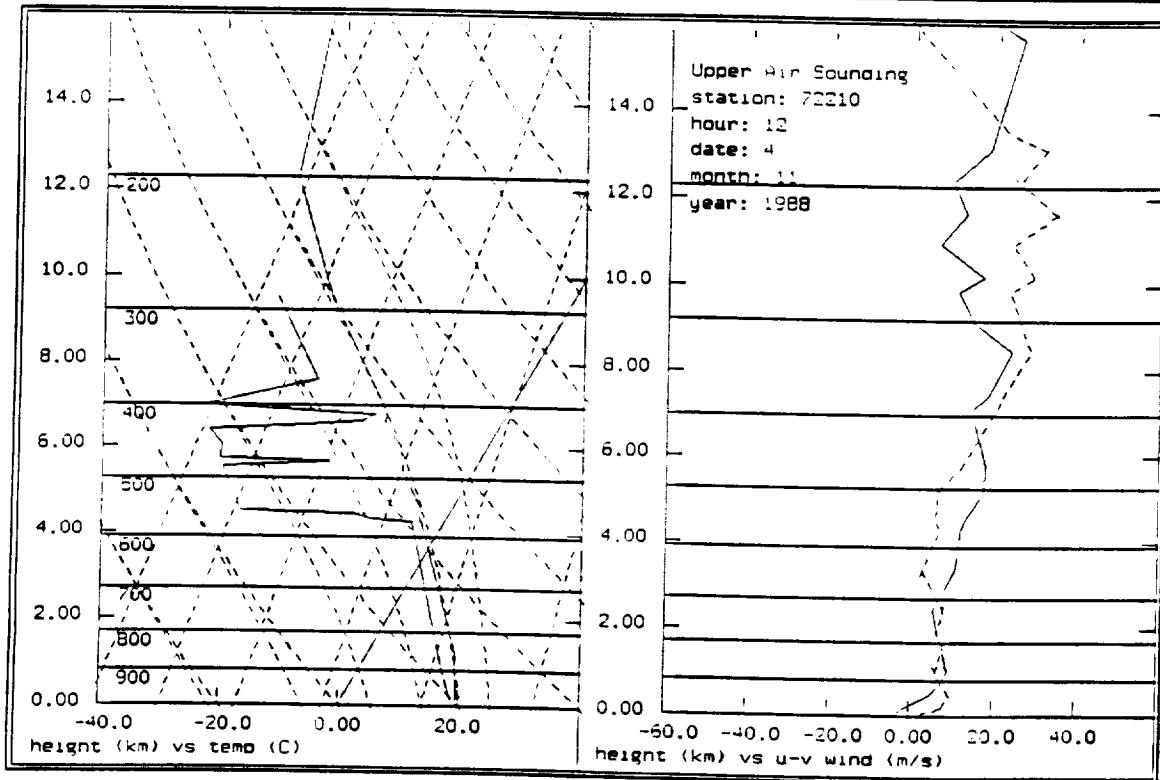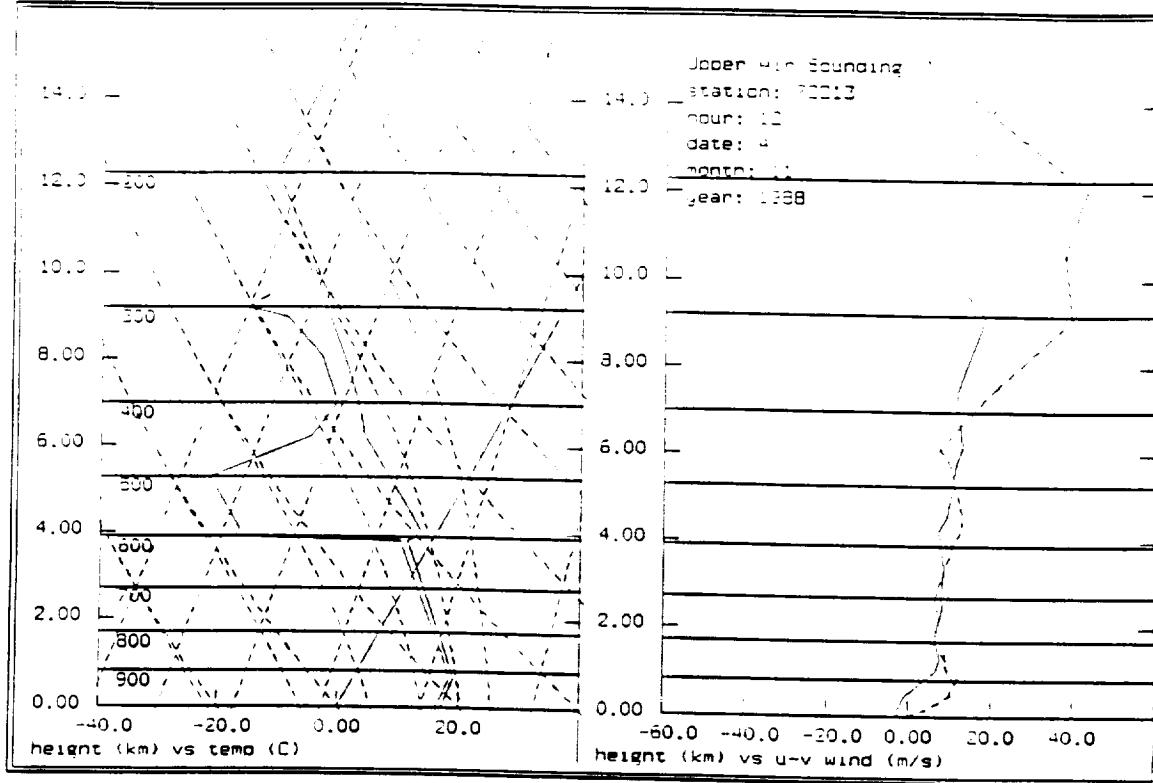
Figure 3: Soundings from Waycross, Georgia (upper panel), and Tampa, Florida (lower panel), for 88309, 1200 Z . The altitudes are derived from a standard atmosphere and are therefore only approximate. In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.
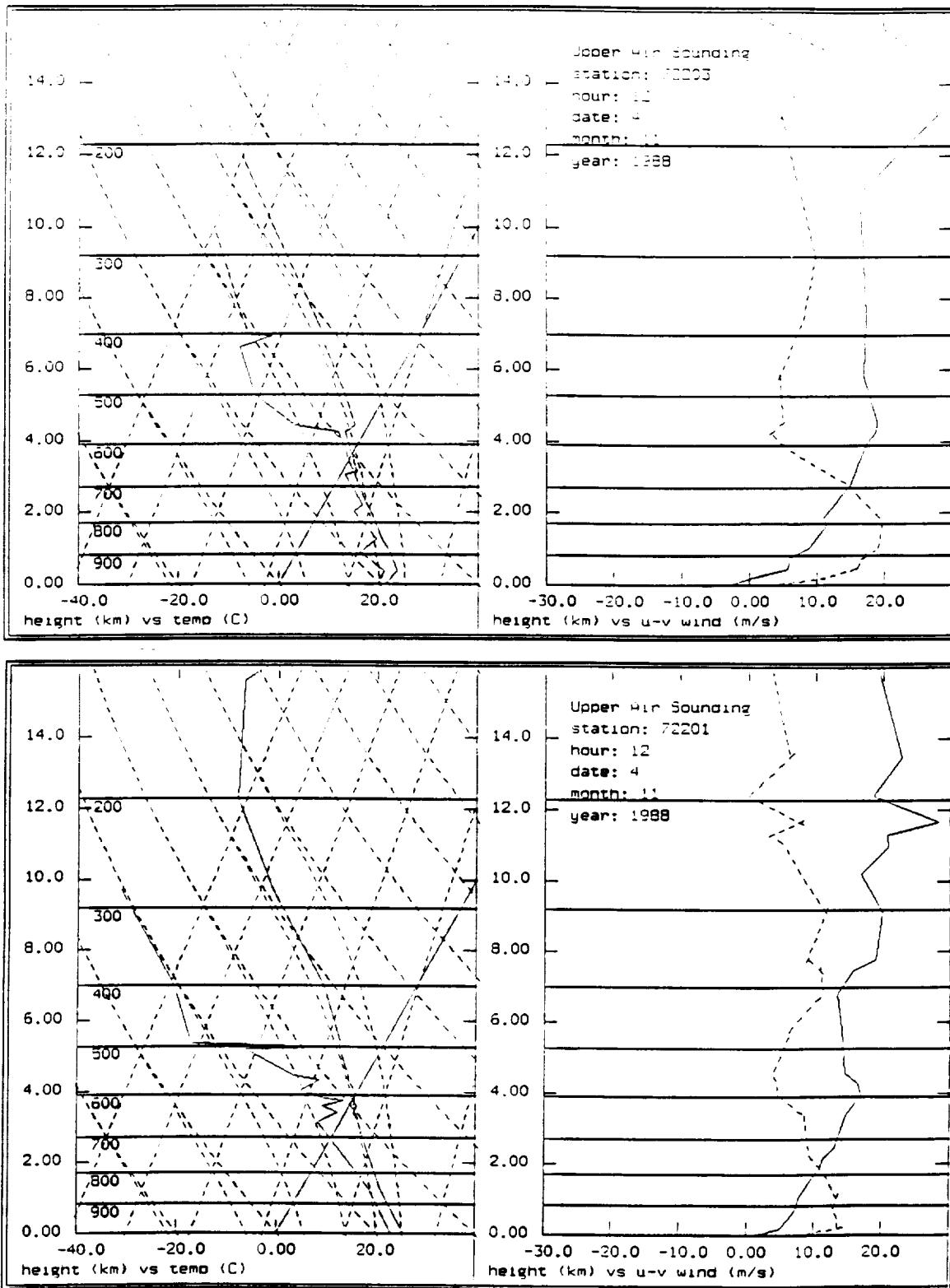
Figure 4: Soundings from West Palm Beach (upper panel), and Key West (lower panel), for 88309, 1200 Z . In the graph of horizontal air velocity vs. altitude, the east component, u, is the solid line and the north component, v, is the dashed line.

4 Cloud Types

The best information we have about the clouds comes from the pilot's (J. W. Bullock's) comments on the voice log that was compiled at the telemetry receiving station. Here are pertinent excerpts concerning the clouds around the most interesting time interval (1325 to 1340 Z).

1308:55	At 11300 ft between cloud decks.
1312:00	Stratus decks very much lower.
1321:05	Large cumulus clouds below me.
1324:55	Lower cloud covering all of CCAFS except partial south of Skid Strip.
1325:45	Now entering cloud again.
1326:15	One minute up and one minute down. Very mixed up situation.
1328:30	At 11300 ft. Clouds going NE.
1341:00	Clouds forming over restricted areas, going toward sea.
1342:30	Breaking out of stratus. Broken deck overhead, 2000 ft thick. One above that. Maybe at 28000 feet.
1343:25	All kinds of situations.
1343:40	Very black southeast.
1348:30	Stratus deck 5 to 6 miles offshore now.
1349:20	Clouds moving from mainland. Some below, some above. Quickly.
1354:50	Two primary decks: 11500 ft, 2000 ft thick. Another at 8000 ft, 1000 ft thick.
1355:30	At 11900 ft.

The clouds were complex and changing rapidly. The primary features appear to be three layers as follows:

1. A high cirrus layer, estimated by the pilot to be at 28,000 ft (8.5 km) altitude. Cloud top heights from the weather radar at KSC show a broad area of tops at about 30,000 ft (9.1 km) whose northwest extremity was just over Cape Canaveral; this layer was in place for the duration of our radar records, which span the interval from 1314 Z to 1354 Z.

2. A broken stratus layer about 2000 ft (600 m) thick whose base was just above the airplane's altitude of about 11,500 ft (3.5 km). This layer was a persistent feature during the flight; the pilot first reported it at 1250 Z, and commented on it a number of times until 1425 Z near the end of the flight.

3. Another stratus layer estimated by the pilot to be 1000 ft (300 m) thick at an altitude of 8000 ft (2.4 km). This deck was first mentioned by the pilot at about 1243 Z and periodically thereafter until 1422 Z near the end of the flight.

Judging from the voice log, the cloud decks above and below the aircraft's altitude of 11,500 ft (3.5 km) extended over much or all of the KSC, Cape Canaveral area sometimes with voids in one or both layers. At 1240 Z The pilot reported clear skies over central Florida, and at 1341 Z he said that the clouds were forming over the restricted areas and then moving toward the sea. These observations agree with the radar estimates of cloud top heights which indicate only a few scattered clouds at distances greater than 20 miles (32 km) west of Cape Canaveral.

There were also some cumulus clouds in the area, and the aircraft flew through some rainshowers during ascent near the beginning of the flight.

5 Electric Field Measurements

From 1125 to 1210 Z, before the flight began, nearly every field mill in the KSC array indicated a widespread region of disturbed electric field with the polarity changing with time and with position. The most intense field was around 7500 V/m at Mills # 14, 19, and 20 near the center of the array. Some discontinuities in the strip chart record from Field Mill # 28 might be interpreted as lightning, but since they did not appear in the records of any other mill, we suspect they are artifacts.

The next episode of disturbed electric field began around 1240 Z and lasted until about 1345 Z. During this time the electric field at the surface increased and decreased very slowly with a broad peak greater than 3000 V/m over Field Mills # 27, 28, 29, 30, 32, and 33, indicating negative charge over the Cape Canaveral area east of the Banana River. No lightning flashes were reported during this time and none are evident in the electric field records. Contours of surface electric field strength at 1330 Z are shown in Figure 5 and values for individual mills are in Table 1. The path of SPTVAR between 1325 and 1340 Z, when it was over the affected mills, is shown in Fig. 6.

The vertical component of the electric field at SPTVAR, E_z, for the whole flight is shown in Fig. 7. Just after takeoff the aircraft encountered electric field strengths up to about 1 kV/m as it passed through some rainshowers between Patrick AFB and KSC. Later

04 November 1988 (88309), 1330 Z, KSC surface E
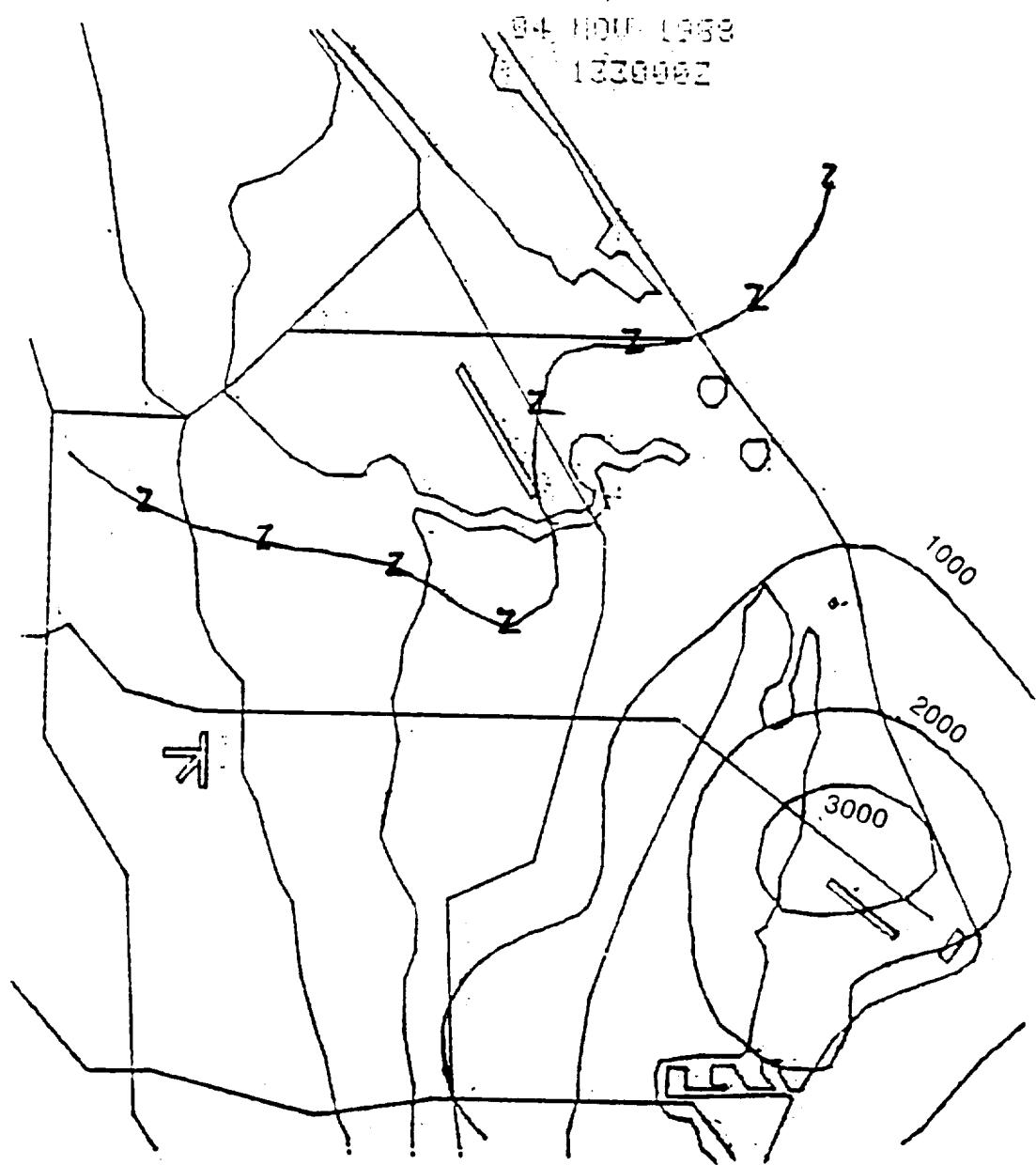
Figure 5: Contours of electric field E derived from the array of electric field meters on the ground at Kennedy Space Center and Cape Canaveral Air Force Station. The values on the contours are in volts/meter. The sign convention here is opposite the original contour plot; our convention is that a positive field implies a negative charge overhead.

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Table 1:

Electric Field at KSC Mills at 1330 Z on 4 Nov. 1988 (88309)
(Negative value means positive charge overhead.)

| Latitude		Longitude		Mill #	E, V/m
deg	min	deg	min		
28	42.23	080	40.17	1	-124
28	41.24	080	43.19	2	-213
28	39.86	080	38.40	4	-185
28	39.48	080	41.99	5	-120
28	38.63	080	40.02	6	-17
28	38.52	080	44.87	7	-258
28	38.52	080	37.34	8	58
28	37.35	080	36.46	9	267
28	36.95	080	41.78	10	-124
28	36.33	080	40.62	11	50
28	36.12	080	38.48	12	319
28	36.12	080	35.40	13	489
28	34.71	080	36.52	14	771
28	34.60	080	38.62	15	437
28	34.51	080	34.43	16	1089
28	33.69	080	40.26	17	20
28	33.30	080	42.15	18	16
28	32.97	080	37.24	19	1020
28	32.50	080	38.69	20	794
28	31.54	080	37.32	21	1487
28	30.38	080	41.61	22	427
28	27.80	080	39.29	23	1070
28	25.79	080	39.81	25	1903
28	32.96	080	34.10	26	1531
28	30.19	080	33.55	27	3022
28	27.35	080	31.55	28	2281
28	27.78	080	35.09	29	3335
28	28.50	080	33.48	30	3469
28	25.90	080	34.59	32	2287
28	24.93	080	36.31	33	1755
28	26.98	080	33.83	34	2138
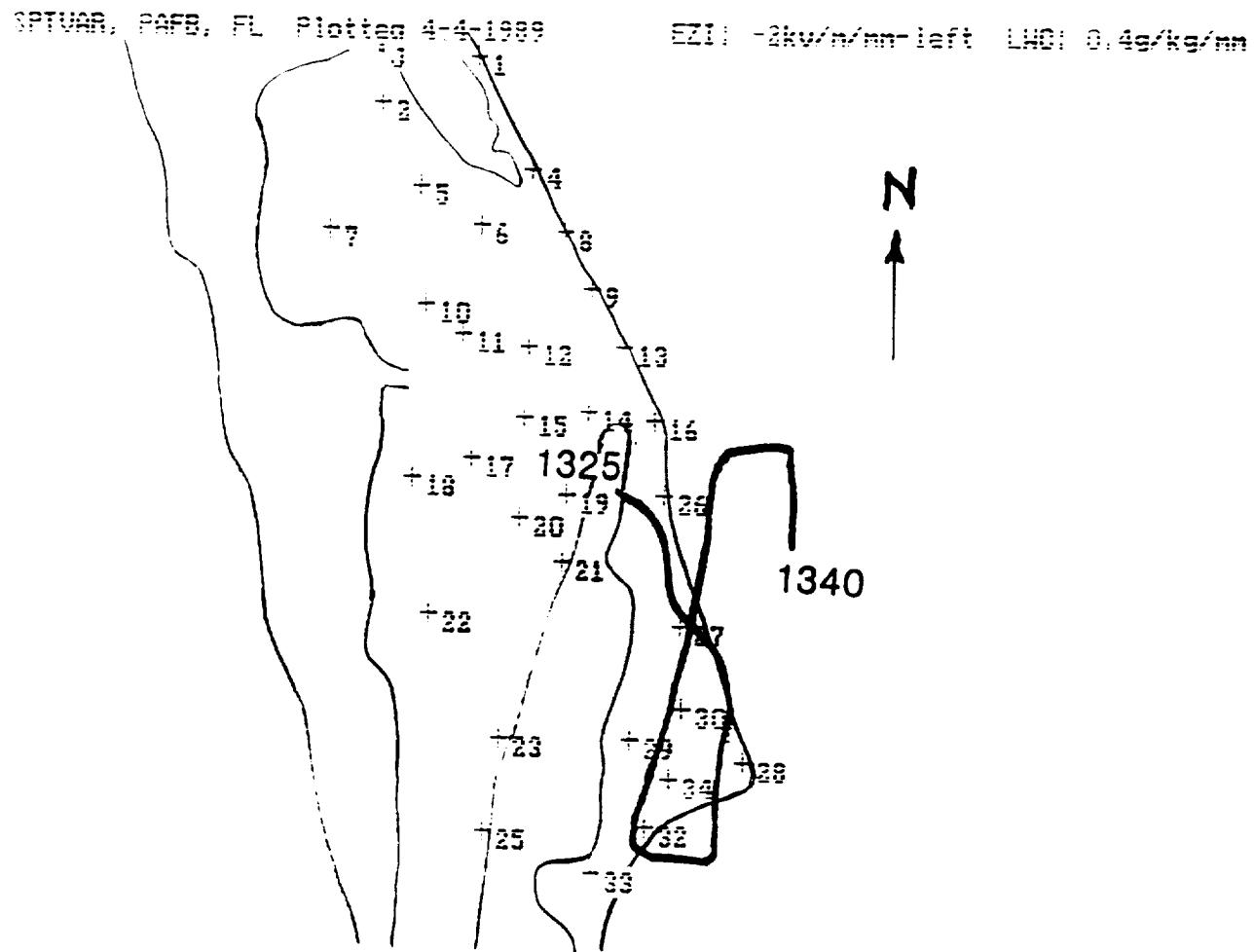
Figure 6: Path of the SPTVAR aircraft over Cape Canaveral from 1325 to 1340 Z on 88309. Field mill locations are also shown.

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in the flight, between 1300 to 1340 Z, the aircraft indicated field strengths greater than 1 kV/m; E_z at SPTVAR during this time is shown enlarged in Fig. 8. The first peak, when E reached about -1 kV/m, occurred when the aircraft was very highly charged and emitting ions via corona discharges, and thus the indicated value of E_z might be higher than the actual value. At the time of this peak SPTVAR was in the vicinity of KSC Field Mill # 4, which indicated $E_z \approx -0.5$ kV/m at the surface.

The other prominent peak in Fig. 8 (at 13.5h, or 1330 Z) is more interesting. SPTVAR was again highly charged and emitting ions via corona discharges, and thus the indicated value $E_z \approx +1.5$ kV/m might again be greater than the actual value. What is significant is that the field mills at the surface below the aircraft indicated an even greater value of E, greater than 3 kV/m in some locations (see Fig. 5). Our interpretation of this situation is given in the next section.

6 Interpretation

The main negative charge in thunderstorms is usually between 0 °C and -20 °C. On day 88309 (4 November 1989) SPTVAR was flying at about 11,500 ft MSL (3.5 km) where the air temperature was about 1 °C, and thus it was at a good altitude to see a strong electric field from the main negative charge without experiencing problems due to icing. Since screening layers are not expected to form at the condensation level in convective updrafts, the main negative charge should not have been masked by screening layers. At 1330 Z (13.5 hours in Fig. 8) the sign of the electric field at SPTVAR indicates a negative charge overhead or a positive charge below or some more complicated distribution. The electric field meters on the ground below SPTVAR also indicated negative charge overhead but the magnitude of the field was greater.

If the field at the ground had been due to negative charge above SPTVAR, then SPTVAR would have been in a more intense field that that at the ground, which was not the case. On the other hand, if the field at the ground had been due to negative charge below the aircraft, then E_z at the aircraft would have been negative, again contrary to the evidence. Several possibilities remain. First, a combination of negative charge above and below the altitude of the aircraft could have resulted in a greater field strength at the ground than at the aircraft. This hypothesis is plausible because the pilot reported cloud layers both above and below the aircraft. Second, it is possible that the field at the ground was the result of charge at an altitude so low that the combination of it and its image charge in the conducting earth produced only a small field at the altitude of the aircraft and that the field at the aircraft was the result of local space charge emitted by coronae at sharp edges on the aircraft.

In order to estimate the magnitude of the charge in the clouds, we constructed simple
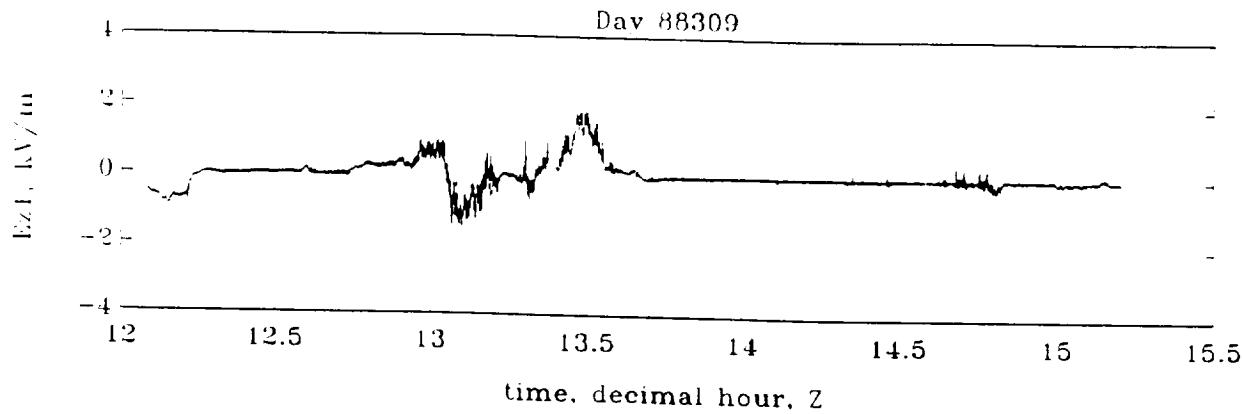
Figure 7: The z component of $\vec{E}$ at SPTVAR for the whole flight on 88309.
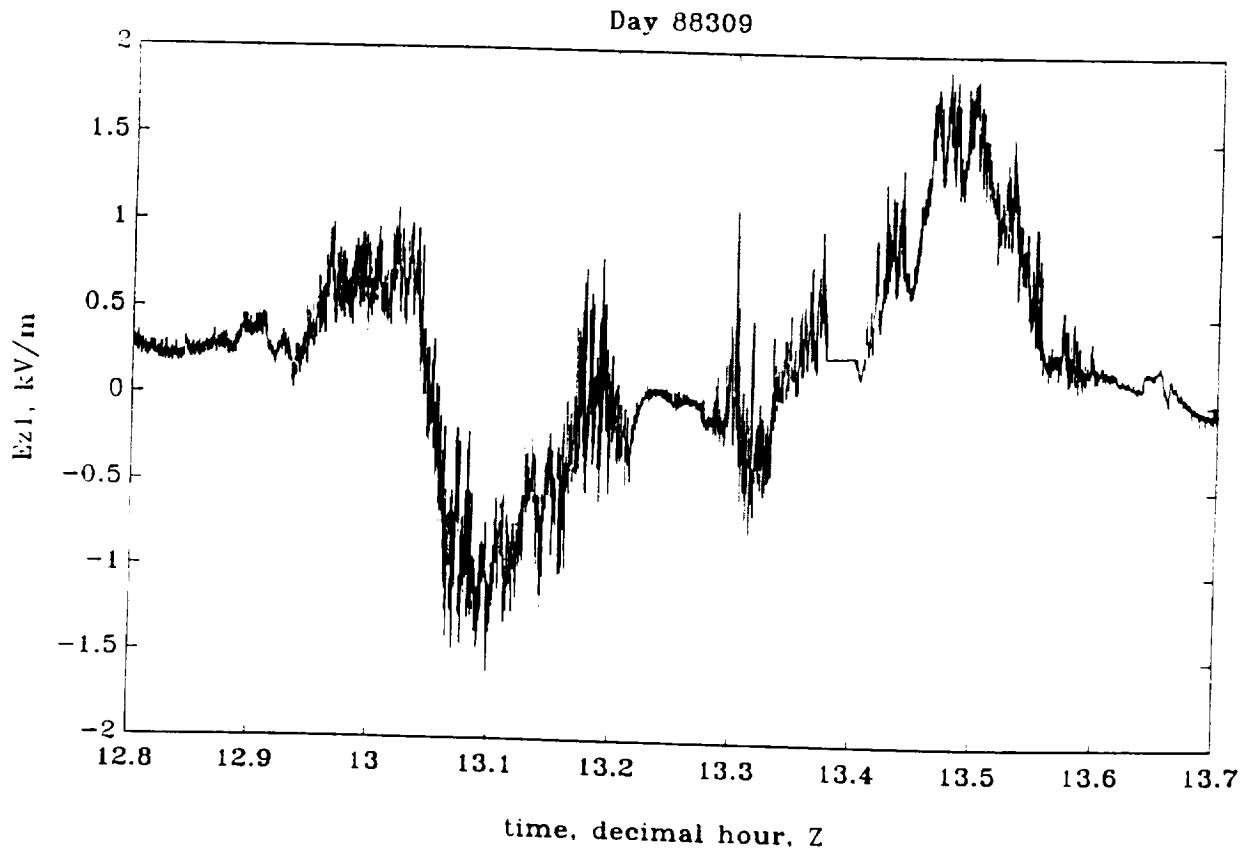

Figure 8: The z component of $\vec{E}$ at SPTVAR during the most interesting segment of the flight.

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models with point charges to try to reproduce approximately the electric field at the surface field mills. This approach was suggested by the relatively simple electric field contours at the surface (Fig. 5). With an intense electric field the surface field mills would see a reduced field because of a layer of space charge from coronae, but on day 88309, the field at the ground was not much above the corona threshold of approximately 3 kV/m (Standler and Winn, 1979). Thus models of charge that neglect the corona space charge layer may not be too much in error. Our best simple model assumed just two point charges plus their image charges below the conducting earth. The positions and magnitudes of the charges were varied to obtain the best fit to the electric field values at the surface field mills. Figure 9 compares the calculated and measured values of E at each of the field mills for the two charges that give the best fit. One charge is 20 C located 1 km NE of Field Mill # 29 at an altitude of 10 km above sea level. The other charge is -6 C located 1 km NW of Field Mill # 18 at an altitude of 13 km above sea level.

These charges obtained with this simple model do not predict the correct values of E at SPTVAR; they predict values somewhat larger than those measured at the surface, whereas SPTVAR saw values about half those at the surface. However, for roughly estimating the total charge over the KSC field mill network, our simple model may be adequate. Most of the lines of force from charges over the network at not too great an altitude will connect to earth in the network. Then, from Gauss's Law, all charge distributions which have the same surface integral of electric field will have the same total charge. In particular, our model of two charges will have the same total charge as the real charge distribution. The total charge in our model is $20 - 6$ C $= 14$ C. This estimate is very rough because of the simplifying assumptions. Furthermore, even if we are close to the correct total charge, there is the possibility that the total could be the sum of a large negative and a large positive charge. This would be the case in situations when a screening layer is well developed; but in the present case, screening layers at the surface, at least, probably do not account for a great deal of charge.

7   Conclusions

From the electric field measurements at the surface alone, we might have predicted a 5- to 10-fold increase in the magnitude of E with altitude, based on the assumption that the charge would most likely reside above an altitude of 3.5 km. On the other hand, judging only from aircraft measurements at an altitude of 3.5 km, we probably would have concluded that there was no significant charge over the KSC area. In fact, the field strength at the aircraft was so small (<1.6 kV/m) compared with what we expect from an electrified cloud, that it did not come to our attention during the flight (see Ms. Maier's comment in the Weather Summary about the lack of any field at the aircraft other than

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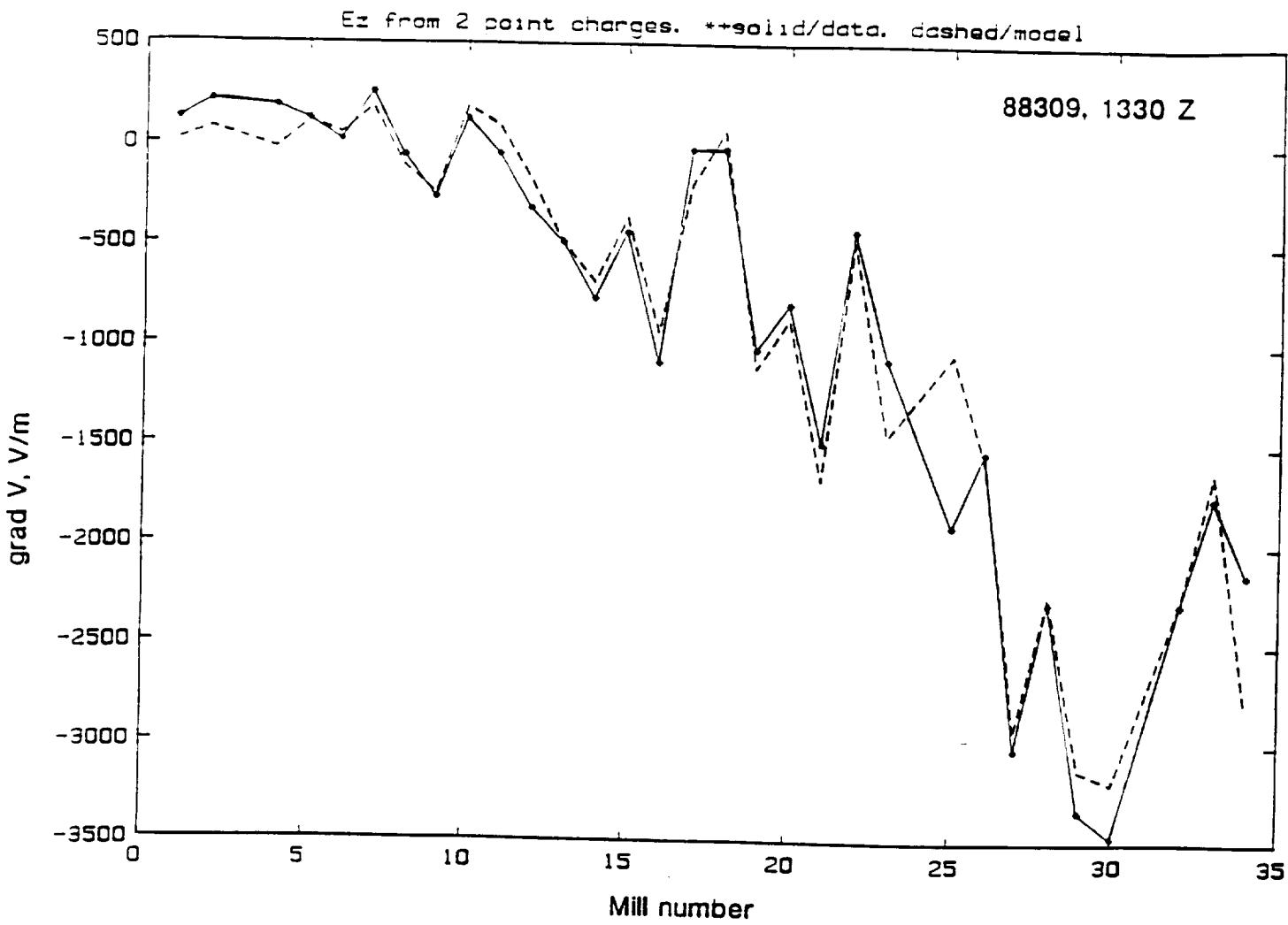
Figure 9: The electric field strength vs. the number assigned to each field mill site on the ground at Kennedy Space Center. The points connected by solid lines are one-minute averages from measurements from the field mills around 1330 Z on 88309. The points connected by dashed lines were derived from a model with two point charges as explained in the text.

fair weather). Measurements with both airborne and surface field mills together give a much better picture of the electrical state of the cloud.

Was the charge in this cloud a significant hazard to rocket operations? Our estimate of the amount of charge is 16 C, which is more than adequate to support a lightning flash (Uman, 1984). However, too little is known about triggered lightning to say whether or not this charge would have responded to a triggering stimulus.

8 Acknowledgments

9 References

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